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Calibration of Underwater Acoustic Transducers at NRL/USRD,

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16h50 - 18h10

SESSION 7: *MEASUREMENT METHODS*
LES METHODES DE MESURE

Chairman: **O. B. WILSON**
Naval Postgraduate School, Monterey, CA, USA

16h50 - 17h30

CALIBRATION OF UNDERWATER ACOUSTIC TRANSDUCERS AT NRL/USRD

CALIBRATION DE TRANSDUCTEURS BASSE FREQUENCE AU NRL/USRD

E. L. VAN BUREN and Joe BLUE,
Naval Research Laboratory, USRD, Orlando, FL, USA

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MEASUREMENTS METHODS FOR LOW FREQUENCY TRANSDUCERS

METHODES UTILISEES AU GERDSM POUR CALIBRER LES TRANSDUCTEURS BASSE FREQUENCE

Christian GIANGRECO, Serge FAURE, Jean François ROSSETTO
GERDSM-DCAN, Toulon, France

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SESSION 8: *CONCLUSION*
CONCLUSION

Summary Remarks by the Conference Chairman, **Bernard TOCQUET**
Thomson-Sintra, Valbonne, France

Résumé et commentaires par le président de la conférence, **Bernard TOCQUET**

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Calibration of underwater acoustic transducers at NRL/USRD

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At the beginning of World War II, the United States recognized the need for establishing systematic methods for calibrating and evaluating sonar transducers and established the Underwater Sound Reference Laboratories. The Underwater Sound Reference Detachment of the Naval Research Laboratory evolved from this beginning and now serves as the focus for underwater acoustic metrology in the United States. It functions as a "National Bureau of Standards for Underwater Acoustics" by providing two

types of reference services for a fee. Calibration, test, and evaluation services and standard transducer loan services cover the frequency range of 0.2 Hz to 2 MHz. This paper describes the calibration, test, and evaluation services. It first covers the measurement facilities for performing the services. Measurement methods for calibrating transducers are then discussed. Next a description of ongoing research in calibration measurement methodology is presented. Finally, some comments are made about calibration system requirements for implementing new measurement techniques.

INTRODUCTION

Prior to the beginning of World War II, the U. S. Navy's capability for calibrating sonar transducers was virtually non-existent[1]. The Office of Scientific Research and Development recognized the need for standards for calibrating sonar transducers and in July 1941 entered into a contract with the Bell Telephone Laboratories (BTL) to supply measurement instrumentation and systems and in March 1942 with the Columbia University Division of War Research to operate the Underwater Sound Reference Laboratories (USRL) located in Mountain Lakes, New Jersey and Orlando, Florida. In 1942 the USRL began to study and test reciprocity calibration concepts that had been independently devised by MacLean[2] in 1940 and Cook[3] in 1941. Standard hydrophones were developed by BTL using piezoelectric crystals of Rochelle salt and ammonium dihydrogen phosphate. BTL developed modified moving-coil sound projectors for the audio-frequency range and piezoelectric crystal sources for the ultrasonic range. This marked the birth of standard underwater acoustic metrology

practices in the United States and of what has become the Underwater Sound Reference Detachment (USRD) of the Naval Research Laboratory.

Bobber gives a summary of the state-of-the-art in underwater acoustic metrology at the end of orld War II as follows:

> At the end of World War II in 1945, it was possible to calibrate a small hydrophone from 2 Hz to 2.2 MHz under ambient environmental conditions. Projectors or sound sources weighing up to a few hundred pounds could be calibrated from about 50 Hz to 140 kHz, with driving powers of 1 1/2 kW available in the audio-frequency range. When pressure was a variable, the capabilities were limited to 2-100 Hz and 100 psi for small hydrophones only, and to 10-150 kHz and 300 psi for fairly small hydrophones and projectors (less than 100 lbs). Standard hydrophones and projectors were adequate, but far from ideal. Stability with time, static pressure, and temperature in many cases was poor for "standard" purposes. Sound sources generally were cumbersome, and response curves were not smooth and flat as is desirable in calibration work. The measuring systems were not capable of pulsed-sound measurements. Good free-field, or unbounded medium, conditions were generally assumed but seldom obtained. Thus, in spite of great strides forward during World War II, the state of the art in 1945 was still relatively crude.

These c.pabilities have been improved upon considerably since that time.

Figure 1 shows an aerial view of the USRD on Lake Gem Mary where its main building was completed in 1951. The pier structure on the lake was also completed about that time. This Lake Facility is one of four facilities

utilized by the USRD in pursuit of its mission. The lake temperature varies during the year between 15° and 30°C. Water in the test wells is separated from the rest of the lake water and from unwelcome marine life by the use of acoustically transparent swimming pool liners and kept isothermal with a bubbler system. There is nothing unusual about this facility. Its primary use is in calibrating the USRD's loan standards prior to shipment to customers. It is also used for outside customers and for in-house research.

Figure 2 depicts our Anechoic Tank Facility, also built in 1951. This 2.5 m-diameter, 7.6 m-long tank can be pressurized to 6.9 MPa (1000 psi). Temperature can be varied from 2 to 40°C. A wide variety of measurements can be made in this tank on submarine and weapons transducers and on anechoic coatings and other acoustic materials. We are presently installing a new larger, extended-range Anechoic Tank (see Fig. 3) that can be pressurized to 20.7 MPa (3000 psi).

Our Low Frequency Facility, built in the 1960's, is used to calibrate hydrophones (or reciprocal transducers in the hydrophone mode). In Fig. 4. we see one of the three calibration tubes that constitute the facility. This tube can be pressurized to 69 MPa (10,000 psi). Temperature can be varied from -2 to 40°C when using a mixture of one part ethylene glycol to two parts water, by volume. The tube has an inside diameter of 20.3 cm and is 274 cm long. The operational frequency range is 1 to 4,000 Hz, with the upper frequency being limited by the first radial resonance mode of the tube. A second tube that is limited to 13.8 MPa also exists in our Low-Frequency Facility. In addition, we have a horizontal tube with a much larger inside diameter of 38.1 cm that is capable of pressures to 69 MPa. We plan to use unidirectional traveling-wave rather than standing-wave measurement techniques almost exclusively in these tubes in the future to be sure of obtaining the

correct hydrophone sensitivity. Since hydrophone evaluation should take into account both pressure and pressure-gradient sensitivity, one must calibrate a hydrophone with the specific acoustic impedance in the tube equal to that for a plane wave in freefield. At present our traveling-wave capability is useable down to about 100 Hz. Ongoing research is investigating the addition of pressure-gradient monitoring hydrophones in the tubes to allow extension of the traveling-wave capability to lower frequencies, possibly to 1 Hz. Use of pressure-gradient hydrophones together with existing pressure monitoring hydrophones should allow a direct measurement of the specific acoustic impedance for establishing traveling wave conditions.

Our Leesburg Facility, which is located in Okahumpka, Florida, has been in use since 1960. A permanent structure was installed there in 1965. This facility is unique in that it is situated on a small spring-fed lake 52 meters deep. There is no main well-head. Water seeps in from numerous places around the walls of the cavity in such a way as to produce no measurable flow noise. Flow maintains the spring at about 22°C at all times of the year. The flow is such that below about 2 meters the water is isothermal with depth. Oxygen content of the water is so low at 5 meters of depth and below that fish are not commonly found at the normal calibration depths used in this facility. The main work load for this facility is the calibration of towed-line array sonars.

Measurement methodology used in USRD's four facilities was, for the most part, developed after World War II. These four facilities have been used in developing the standard transducers that are available on a loan basis from the USRD, are used in research for new standard transducer and methodology development, and are used widely by the USRD, and other U. S. Navy laboratories and contractors in their development of sonar transducers and

underwater acoustic materials. In addition these facilities and standards are made available to any non-naval U. S. institution or industry with the need for standards or calibration of underwater acoustic devices. Arrangements can be made by NATO countries to utilize these services through agreements with the U. S. Naval Sea Systems Command (NAVSEA) or through U. S. subsidiaries of NATO country companies. This paper discusses how primary underwater acoustic standards are calibrated. The calibration of secondary standards, "standard" projectors, evaluation of sonar transducers, and calibration systems are also discussed.

I. CALIBRATING THE PRIMARY STANDARDS

Even though the USRD has about 1800 transducers (hydrophones, reciprocal transducers, and projectors) of about 40 different types in its standard loan inventory, we only consider hydrophones, i.e., transducers used solely as hydrophones, to be suitable for primary standards. In particular, we only consider those hydrophones that maintain stable sensitivity over large temperature and pressure ranges and over a long time to be suitable for standards. The other transducers that we maintain are either necessary in calibrating the primary standards or in enabling customers to meet some of their specialized requirements for acoustic measurement, test, and evaluation.

There are three methods for calibration in use at the USRD for absolute calibration of primary standard hydrophones. They are: 1) free-field reciprocity calibration, 2) coupler reciprocity calibration, and 3) the two-projector null method of calibration.

Free-field reciprocity methods are used in the Lake and Leesburg Facilities down to about 100 Hz. Below 100 Hz lack of a suitable robust reciprocal transducer limits this technique. In the Anechoic Tank Facility the

free-field reciprocity method is used down to abut 2 kHz. A discussion of free-field reciprocity including phase calibration from Luker and Van Buren[4] is reproduced here.

The hydrophone calibration procedure described here is an extension of conventional three-transducer reciprocity calibration[1] to include phase. Use of this procedure requires three transducers (a projector P, the hydrophone H to be calibrated, and a reciprocal transducer T that can be used as both a hydrophone and a projector). A series of three projector-hydrophone measurements are made using either P or T as a projector and H or T as a hydrophone. The measurements are made under free-field conditions with the hydrophone located in the farfield of the projector. The three experimental setups are indicated in Fig. 5. The input current and output voltage values are complex, i.e., they include both amplitude and phase. The input currents in setups 1 and 2 are chosen to be identical. In this case i_p does not appear in the final expression for the sensitivity of the hydrophone and need not be measured.

For setup 1 the farfield pressure p_{PH} produced at H, which is located d_1 meters from P, is

$$p_{PH}=(i_P S_P d_0/d_1)\exp[jk(d_0-d_1)], \tag{1}$$

where S_P is the transmitting current response of P and d_0 is the reference distance, normally equal to 1 m, at which the transmitting pressure is specified in the definition of S_P. The wavenumber k is equal to ω/c, where ω is the angular frequency in radians per second and

c is the sound speed in the surrounding medium in meters per second. The assumed time dependence $\exp(j\omega t)$ has been suppressed for convenience. The open-circuit voltage produced by H is given by

$$e_{PH}=M_H p_{PH}=(M_H i_P S_P d_0/d_1)\exp[jk(d_0-d_1)], \tag{2}$$

where M_H is the receiving voltage sensitivity of H.

Similarly, we obtain for setup 2:

$$e_{PT}=M_T p_{PT}=(M_T i_P S_P d_0/d_2)\exp[jk(d_0-d_2)], \tag{3}$$

where M_T is the receiving voltage sensitivity of T. Combining Eqs. (2) and (3) yields

$$e_{PH}/e_{PT}=(M_H d_2/M_T d_1)\exp[jk(d_2-d_1)]. \tag{4}$$

Since T is a reciprocal transducer, we have $M_T=JS_T$, where J is the complex spherical wave reciprocity parameter given by Beranek[5] as

$$J=(4\pi d_0/j\omega\rho)\exp(jkd_0), \tag{5}$$

where ρ is the density of the surrounding medium. From setup 3 we obtain

$$e_{TH}=M_H p_{TH}=(M_H i_T S_T d_0/d_3)\exp[jk(d_0-d_3)]. \tag{6}$$

Combining Eqs. (4) and (6) with the use of Eq. (5) produces the following expression for the receiving voltage sensitivity of the hydrophone H:

$$M_H=\{[4\pi e_{PH}e_{TH}d_1d_3)/(j\omega\rho e_{PT}i_Td_2)]$$

$$\times\exp[j(\omega/c)(d_1+d_3-d_2)]\}^{1/2}. \quad (7)$$

Standard practice at the USRD and elsewhere in the United States is to ignore the phase calibration and do magnitude calibration only. The distances d_1, d_2, and d_3 in this case are usually all the same. For phase calibration using free-field reciprocity the discussion by Luker and Van Buren continues:

> The difficulty in determining the phase of M_H using this method lies in accurately determining both the sound speed and the measurement distances d_1, d_2, and d_3. For example, at 100 kHz in water an error of only 1 mm in any one of the distances gives a phase error of about 12°. However, we can avoid this difficulty by positioning all three transducers P, H, and T in a straight line with H located between P and T. This assures that $d_2=d_1+d_3$. Then Eq. (7) simplifies to
>
> $$M_H=[(4\pi e_{PH}e_{TH}d_1d_3)/(j\omega\rho e_{PT}i_Td_2)]^{1/2}. \quad (8)$$
>
> Since the distances and sound speed no longer appear explicitly in a phase term in Eq. (8), the accuracy of the phase of M_H calculated using Eq. (8) is limited only by the accuracy of the phase measurements of the voltages and current.

Phase calibration experiments[4] have proven the feasibility of this method, and new computer-controlled calibration systems being developed at the USRD will have the capability of making on-line complex calibration measurements. These measurements will become routine after the required specialized rigging is further developed and as experience is gained through additional experiments.

In the Low Frequency Facility, reciprocity couplers, such as shown in Fig. 6, are used in the absolute calibration of hydrophones over the frequency range from 10 Hz to 8 kHz, the temperature range from -2 to 35°C, and the pressure range from 0 to 105 MPa (15,000 psi). The two-projector null method, as illustrated in Fig. 7, has been used in the USRD's low frequency tubes for the absolute calibration of hydrophones from 0.2 to 20 Hz. In this method the two projectors are driven electrically with a provision for controlling the relative phase and amplitude of the two drives. The input to a moving coil projector is adjusted in amplitude and phase until a null pressure is obtained at the hydrophone. Further details of these method can be found in the book by Bobber[1].

Each of USRD's four calibration facilities calibrates its own primary standard hydrophones using the appropriate methods. This is done on a quarterly basis. Any discrepancy from previous calibrations is thoroughly investigated and cross checked by comparison calibration in other USRD facilities. Semi-annually an H52 standard hydrophones is sent in turn to each of the four facilities for calibration over their range of capabilities. Results are compared, and facility differences are resolved. In this manner the USRD maintains a higher degree of calibration accuracy and confidence than is possible with one facility alone. This confidence is important in setting underwater acoustic metrology standards for the United states

II. SECONDARY CALIBRATIONS OF STANDARD LOAN HYDROPHONES, PROJECTORS, AND RECIPROCAL TRANSDUCERS

For economic reasons, all loan standards available from the USRD are calibrated secondarily using the USRD primary standard hydrophones which are calibrated quarterly. All of the standard types used by the USRD have been carefully developed and individually tested over environmental conditions that move than cover their range of intended use. The USRD Transducer Catalog[6] describes most of the standard transducers available to its customers.

The standard loan transducers are routinely calibrated at the USRD Lake or Leesburg Facility. Routine calibration entails using pulsed or continuous wave swept frequency secondary calibration methods at two different separation distances under good free-field conditions. Two separations are used to ensure that the transducers are responding properly to the pressure field. Failure of the transducer response to follow the inverse spreading law for spherical waves may imply improper farfield conditions or an inappropriate pressure-gradient sensitivity of the transducer, among other possibilities. Rigging has been carefully designed so as not to appreciably affect the calibration, and care is taken to see that there are no bubbles adhering to the transducers. Most transducers used in United States calibration facilities are loan standards calibrated by secondary methods. Some facilities perform freefield reciprocity calibration on their own or USRD standards. However, most Naval activities insist on maintaining traceability of their underwater acoustic measurements to the USRD since the USRD maintains traceability of its basic measurements used in setting underwater acoustic standard to the National Bureau of Standards. Just as some measurements done at the National Bureau of Standards result in an "accepted value" being assigned to a standard, measurements on standard underwater acoustic

transducers at the USRD result in "accepted calibration curves" being assigned to those transducers. In this manner, secondary calibration of standard hydrophones loaned to a wide variety of customers sets underwater acoustic metrology practices for the United States.

III. EVALUATION OF SONAR TRANSDUCERS

Facilities at the USRD are also available for calibration, test, and evaluation of sonar transducers and arrays. These facilities have served the Navy well in the development of transducers and arrays for a wide range of applications. In particular, the Low Frequency Facility has aided development of reliable hydrophones for long range surveillance systems. The Anechoic Tank Facility has advanced the development of torpedo and various submarine transducers. The Leesburg Facility has been involved with practically every towed-line array sonar in the Navy. However, the USRD Facilities are not adequate to handle all of the U.S. Navy's sonar calibration, test, and evaluation. Other Navy Laboratories have small calibration facilities such as Dodge Pond and the indoor test pool at the Naval Undersea Systems Center (NUSC) and TRANSDEC at the Naval Ocean Systems Center (NOSC). The Naval Weapons Support Center performs calibration measurements on sample lot units from production runs of fleet sonar transducers. The Navy also maintains three Transducer Repair Facility calibration facilities at Navy shipyards. In addition, to make some of the sonar calibration, test, and evaluation measurements that are not possible in small bodies of water, NUSC maintains a facility with a water depth of about 200 m at Lake Senaca in New York and NOSC maintains a capability at the David Taylor Naval Ships Research and Development Center's Lake Pend O'reille 400 m-deep facility. In general, these facilities provide their own electronic calibration equipment but for

the most part rely on techniques developed by and standards supplied by the USRD.

Bobber[1] has done an excellent job of covering calibration practices at the USRD up to 1970. In this paper we will discuss measurement methodology that has been developed since that time or is presently being developed. Much of the newer methodology was developed in order to allow lower-frequency calibration measurements in the multipath-limited environment of small facilities and is facilitated by new digital signal processing techniques involving analog-to-digital converters and computers.

An example of newer digital techniques replacing older analog ones is in immittance measurements. Bobber's[1] description of the apparatus and techniques for high level signal measurements is as follows:

> One technique that has been used successfully is illustrated by the simplified diagram in Fig. 8. The transducer voltage or current pulse is sampled by a step-down current transformer consisting of a toroid coil surrounding a single conductor. Simultaneously, the signal in a continuous-wave reference circuit is sampled. The two signals are added and displayed on a cathode-ray oscilloscope. The reference signal contains only the fundamental frequency. The amplitude and phase of the reference signal is adjusted until a null condition in the steady-state part of the pulse is observed on the oscilloscope. Then the reference signal is equal in amplitude and opposite in phase to the fundamental frequency component of the transducer signal pulse. There will be a signal residue in the null because of the harmonic distortion frequencies in the signal. If the harmonic distortion is small, the residue is small and does not introduce measurable error in the nulling

technique. If the residue is large, a low-pass filter is used to attenuate the harmonic frequencies.

The three transformers should be identical to minimize errors. In practice, the current and reference signal transformers can be one and the same.

The reference circuit is a low-signal continuous-wave circuit. The reference voltage and current are readily obtained by conventional calibration methods. Phase difference between the reference current and voltage is controlled and measured by the phase shifter.

Using this null-balance technique, immittance and sound pressure levels in the water were measured as a function of input power in order to provide an indication of the linearity of a sound projector. In cases where there existed appreciable harmonic distortion, a high degree of accuracy could not be obtained from this null-balance technique. Newer techniques used at the USRD involve digitizing the input voltage, current, and standard hydrophone voltage waveforms and using Fast Fourier Transforms (FFT) in immittance and linearity calculations. These techniques involve sampling of continuous waves or pulsed sinusoids at rates that are multiples of or that are integrally related to the driving frequency thereby assuring a spectral line component in the FFT at the driving frequency. Immittance is then easily calculated by ratios of FFT's.

Use of digital computers in calibration systems has led to consideration of calibration techniques that do not require steady state signal conditions. One such technique investigated at the USRD by Beatty, George, and Robinson[7] is the Prony method. For a transducer to be capable of being calibrated by using the Prony method, it must be representable as a linear point or "lumped"

device which can be described by a Laplace Transform. Data used in the Prony method must be acquired before the signals are contaminated by boundary reflections. Early work on the Prony method involved reciprocity calibration in the USRD's Lake Facility.[7] Traditional reciprocity calibration measurements in this facility use pulsed sinusoids to gate out boundary reflection interference and have a low-frequency limit of about 500 Hz. Using two USRD Type J11 reciprocal transducer and a USRD Type H56 hydrophone, the experimental waveforms shown in Fig. 9 were acquired and used, via the Prony method, to calculate the amplitude and phase calibration curve shown in Fig. 10. These results show excellent agreement with calibration values obtained in USRD's Low Frequency Facility down to about 25 Hz. Work is still ongoing to develop methods for making accurate measurements in the USRD's Anechoic Tank Facility (and indeed in any measurement facility) where there is a requirement to determine the transmitting voltage and current response of low-frequency high-Q sonar projectors at resonance where steady state cannot be reached before wall reflections interfere. (Our so-called Anechoic Tank is not anechoic at low frequencies.) The wide variety of methods being explored for making these so-called reverberation-limited measurements are depicted in Fig. 11.[8-10] Included are both the stepped-sinusoid input case where the intent is to determine the steady-state amplitude and phase response one frequency at a time and the broad-band transient input case where a significant portion of the transducer transfer function is obtained from a single measurement. It is not expected that one method will be appropriate for calibration of all transducers. Rather a family of methods will be required to handle the broad range of transducer types, Q values, frequency ranges, and boundary reflection conditions.

Sonar array calibration has received quite a lot of attention in the United States. Calibration techniques have been investigated for both line arrays and area arrays.

The USRD's Leesburg Facility is involved in developing procedures for calibrating towed-line array sonar in open-water. Measurements on hydrophones in a long line are not always as simple as measurements on standard hydrophones. Towed-line arrays are designed primarily to detect, at sea, a plane wave from a distant target impinging on their acoustically sensitive length. Measurements at the Leesburg Facility usually are made with the line suspended vertically, but establishment of a plane wave over the entire acoustically active length is not possible. An element-by-element calibration is made by suspending the line or a line segment in the water and insonifying, in turn, each element with a plane wave. if the line array is acoustically transparent, and if it is properly rigged, the calibration is performed by the usual straightforward comparison method used for small hydrophones. Typical calibration results are shown in Fig. 12. For most lines, the length of a hydrophone grouping in the line is short enough to allow a plane wave to be established over the hydrophone length. As seen in Fig. 13, the rest of the line, however, generally is not in a plane-wave field. It is difficult, if not impossible, to shield acoustically the inactive portion of the line at the low frequencies that are involved. If the line is not acoustically transparent, acoustic excitation of the nonreceiving portion of the line by the non-planar-wave field that exists there may cause some difficulties. For example, longitudinal and transverse modes of vibration of the line may be excited that would not be excited by a plane-wave. These modes can cause non-acoustic pressure fields in the vicinity of the hydrophone elements and can thus significantly affect the calibration. When acoustic excitation of the

nonreceiving portion of the line occurs, results such as those shown in Fig. 14 are obtained. We note that low-frequency undulations appear in the 1 m data, but that the data at 3m and 5m produce relatively smooth, and coincident, results. The shapes of the curves at low frequencies vary from element to element, depending upon element position in the line, but symmetrically placed elements have almost identical low-frequency undulations. When two towed-line array segments are joined, results identical to those in Fig. 14 are obtained, which indicates that the low-frequency undulations are due to longitudinal rather than transverse vibrations. This conclusion is further substantiated by the fact that hanging weights varying from 15 to 500 lbs on the lower end of the line does not make much difference in the low-frequency undulations.

When the hydrophone grouping length in a towed-line array is too long to allow far-field measurements to be made under free-hanging vertical conditions, the line can be bent around a hoop and the hydrophone group can be calibrated with a sound source aimed at the center of the hoop as shown in Fig. 15. If the line is too long for a hoop, it can be coiled on an acoustically transparent reel and calibrated with the sound source suspended in the center of the reel, as shown in Fig. 16. Results for lines that can be calibrated free hanging, on a hoop, or on a reel verify the validity of these techniques.

Efforts to provide specialized tube calibration devices for towed-line arrays have been undertaken. Zalesak and Trott[11] investigated a towed-line-array calibrator, as depicted in Fig. 17. This calibrator consists of a water-filled open tube with two tubular drivers to produce a nearly uniform sound field within the tube and one tubular hydrophone as a calibrated monitor. Comparison calibration of short elements of some towed-line arrays

can be performed by threading the array through the tube and centering the elements (or hydrophone groupings) one by one in the tube. This device works very well for arrays that have short hydrophone groups and that are not excited significantly by the large drop in acoustic pressure at both ends of the tube. However, most towed arrays have hydrophone groupings that are long compared to the length of the uniform sound field that could be produced by this device. Zalesak and Rogers[12] developed a method for producing a sound field in a long tube that can be made to appear as a plane-wave incident at any direction to a towed array placed in the tube. Fig. 18 illustrates this device. The tube wall contains projector-hydrophone pairs located along the entire length of the tube with center-to-center spacing less than about one-sixth of a wavelength. Before setting up the desired sound field at any given frequency, the projectors are driven, one-by-one, and the complex received voltage outputs of all the hydrophones are recorded. This results in a transfer matrix that is inverted. The inverse can then be used to determine the amplitude and phase with which to drive each projector for any desired plane-wave direction. The response of a line array that is located in the tube is then identical to the corresponding response of the array in open water. By varying the angle of incidence, the entire directivity patterns can be determined. A 9.1 m (30 ft) long tube is in limited use for this purpose at the USRD. Recent results obtained using this tube are described in Ref. 13. An effort to develop a 91 m (300 ft) long tube calibrator (called the long-line-hydrophone calibrator) at the Leesburg Facility is presently underway.

Problems in calibrating large transducers and transducer area arrays where farfield conditions cannot easily be achieved in compact calibration facilities have received considerable research attention since the early

1960's. One result of this research was the development of two independent methods for obtaining farfield responses from nearfield measurements. Bobber[1] reviews both methods, the DRL Method and the Trott Nearfield Calibration Array (NFCA) Method, and discusses their limitations. Some of the limitations of the DRL method have been overcome with the advent of faster and cheaper computers. This Helmholtz type of approach is also finding application in examining the total pressure field from the nearfield to the farfield produced by vibrating objects.

The Trott NFCA is a large area array of small reciprocal transducer elements that are arranged in a grid that is usually rectangular. The relative acoustic outputs of the elements are selected so that the array, when driven as a projector, produces a nearly uniform plane wave in a specified direction over a volume in its nearfield and over a wide frequency range. As a receiver the NFCA is a plane-wave filter to sound originating from a projector or scatterer located in the nearfield volume, i.e., the NFCA response is proportional to the farfield pressure distribution of the transducer or scatterer for the direction opposite to the plane wave.

Several Trott planar NFCA's were constructed in the late 1960's, but to our knowledge none of them are still operational. Two large planar NFCA's are presently being constructed, one for use as a projector in NRL's target characteristics measurement facility in Washington, D.C., and one for use as both a projector and a receiver in the USRD Leesburg Facility. Van Buren[14] investigated cylindrical NFCA's using only a single line array of transducers. The NFCA is synthesized by rotating the test transducer near the line; making measurements of the response of the line at discrete angular positions corresponding to line locations in the cylindrical NFCA, and synthesizing the cylindrical array response using a calculator or computer to perform the

calculations. This technique was implemented for the Anechoic Tank Facility using a 1.19 m-long line to achieve an upper frequency capability of about 50 kHz, a factor of 5 higher than previous NFCA's.[15] Fig. 19 shows the results of a calibration using this line. More recently, the NFCA concept was extended to a synthetic spherical configuration (Fig. 20) that provides full three-dimensional beam patterns of enclosed transducers or scatterers with a single 360° rotation of a semi-circular arc line array of hydrophones.[16]

With the advent of large area hydrophones designed to reduce flow noise in receiving arrays, the need arises to determine the response of area hydrophones to hydrodynamic pressure fields with non-acoustic wavenumbers. To address this need, we are investigating the use of a piezoelectric polymer array to produce the required wavenumbers evanescently. Fig. 21 shows such an array using a striped-electrode pattern with independent drive for each stripe. Calculations have shown that no appreciable acoustic energy should radiate to the farfield of the array when the phasing between the drive of neighboring stripes corresponds to wavenumbers above the acoustic region, i.e., non-acoustic wavenumbers. Experimental results obtained with a 12.5 cm X 12.5 cm square prototype wavenumber calibrator show that single wavenumber non-acoustic pressure fields can be obtained.[17]

In order to better implement calibration methodology now in use and new methodology being developed, new digital calibration systems are needed. Figure 22 shows a new precision measuring system (PMS) under development at the USRD. Key components to the system include 4 channels for simultaneously measuring signals using 5 MHz, 12-bit analog-to-digital converters, a built in self- calibration system to calibrate the signal channels including the A/D converters, 2 transmit channels for projecting sound into the water, timing circuitry, signal generation section, a computer for controlling the system,

an optional array processor for rapidly handling array calculations, and a host computer for further computations, data storage, and report generation.

There has been a recent trend in the United States toward fewer calibration facilities. As calibration methodology becomes more complex, systems more complex and costly, and facility maintenance more costly, we expect this trend to continue.

REFERENCES

1. R. J. Bobber, Underwater Electroacoustic Measurements, U. S. Government Printing Office, Washington, D. C., July 1970. (Not in print. Available from NTIS).

2. W. R. MacLean, "Absolute measurement of sound without a primary standard," J. Acoust. Soc. Am. 12, 140-146 (1940).

3. R. K. Cook, "Absolute pressure calibration of microphones," J. Acoust. Soc. Am. 12, 415-420 (1941).

4. L. D. Luker and A. L. Van Buren, "Phase calibration of hydrophones," J. Acoust. Soc. Am. 70, 516-519 (1981).

5. L. L. Beranek, Acoustic Measurements, Wiley, New York (1949).

6. USRD Transducer Catalog, April 1982, Naval Research Laboratory, Underwater Sound Reference Detachment, P. O. Box 8337, Orlando, FL 32856, USA.

7. L. G. Beatty, J, D. George, and A. Z. Robinson, "Use of the complex exponential expansion as a signal representation for underwater acoustic calibration," J. Acoust. Soc. Am. 63, 1782-1794 (1978).

8. J. D. George, V. K. Jain, and P. L. Ainsleigh, "Estimating steady-state response of a resonant transducer in a reverberant underwater environment," Proc. IEEE ICASSP-88, April 1988.

9. J. D. George and P. L. Ainsleigh, "A constrained Newton algorithm for maximum likelihood modeling of sums of exponentials in noise," Proc. IEEE ICASSP-90, April 1990.

10. J. D. George and P. L. Ainsleigh, "Stepped sine response modeling using noisy sampled data," NRL Memorandum Report No. 6644, June 1990.

11. J. F. Zalesak and W. J. Trott, "Low-Frequency technique for the underwater calibration of individual elements of a line hydrophone array," J. Acoust. Soc. Am. 62, 91-101 (1977).

12. A description of this method is given in the reference by L. D. Luker, J. F. Zalesak, C. K. Brown, and R. E. Scott, "Automated digital benchtop calibration system for hydrophone arrays," J. Acoust. Soc. Am. 73, 1212-1216 (1983).

13. L. D. Luker and J. F. Zalesak, "Free-field acoustic calibration of long underwater acoustic arrays in a closed chamber," submitted to J. Acoust. Soc. Am.

14. A. L. Van Buren, "Cylindrical nearfield calibration array." J. Acoust. Soc. Am. 56, 849-855 (1974).

15. A. L. Van Buren, M. D. Jevnager, and A. C. Tims, "A 5-to 50-kHz synthetic cylindrical nearfield calibration array," J. Acoust. Soc. Am. 77, 1927-1932 (1985).

16. A. L. Van Buren, "Spherical nearfield calibration array for three-dimensional scanning," J. Acoust. Soc. Am. 85, 2655-2660 (1989).

17. D. H. Trivett, L. D. Luker, S. Petrie, A. L. Van Buren, and J. E. Blue, "A planar array for the generation of evanescent waves," J. Acoust. Soc. Am., in press, (1990).

FIGURE CAPTIONS

Fig. 1. Aerial view of USRD.

Fig. 2. Anechoic Tank Facility.

Fig. 3. Extended Range Anechoic Tank.

Fig. 4. System J.

Fig. 5. Measurement setups for freefield reciprocity calibration.

Fig. 6. Typical reciprocity coupler.

Fig. 7. Two-projector null calibration.

Fig. 8. Electronics for analog immittance measurements.

Fig. 9. Prony method waveforms.

Fig. 10. H56 sensitivity (amplitude +; phase).

Fig. 11. Methods being explored for making accurate reverberation-limited measurements.

Fig. 12. Sensitivity of a towed-line array hydrophone.

Fig. 13. Incident spherical wavefield.

Fig. 14. Apparent sensitivity of a towed-line array hydrophone.

Fig. 15. Hoop-rigged towed-line array.

Fig. 16. Reel-rigged towed-line array.

Fig. 17. Tube calibrator for towed-line array hydrophones.

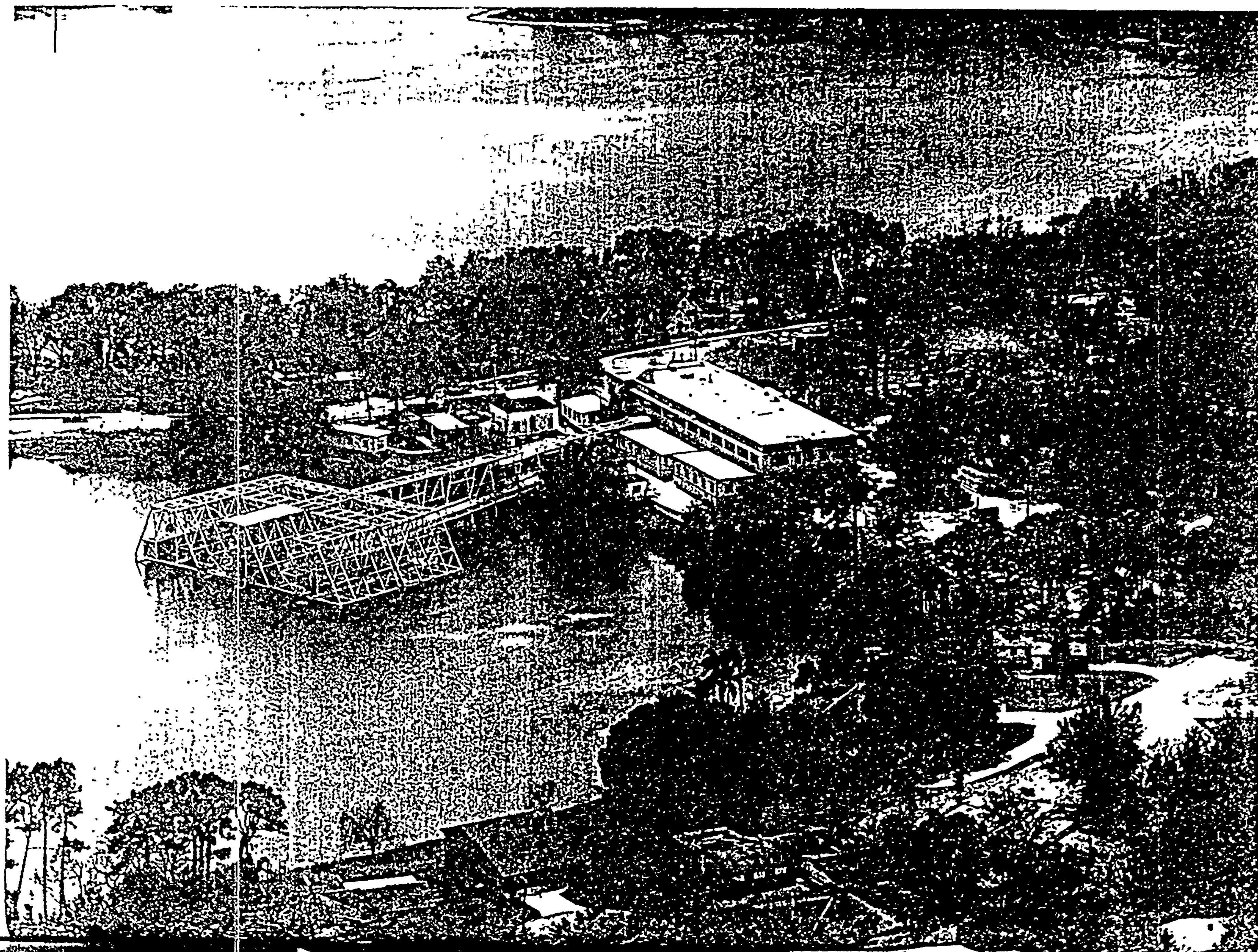
Fig. 18. Tube calibrator for towed-line arrays.

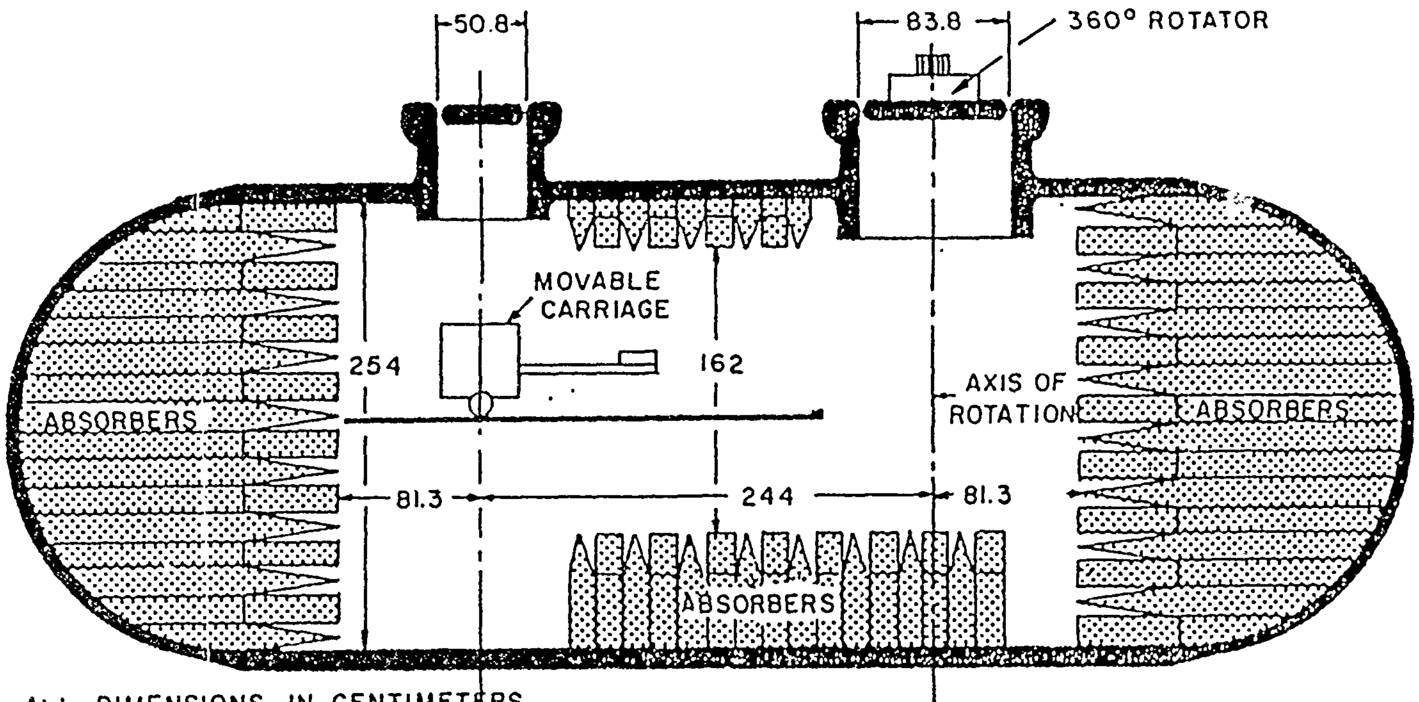
Fig. 19. Beam pattern obtained using the NFCA.

Fig. 20. Synthetic spherical NFCA.

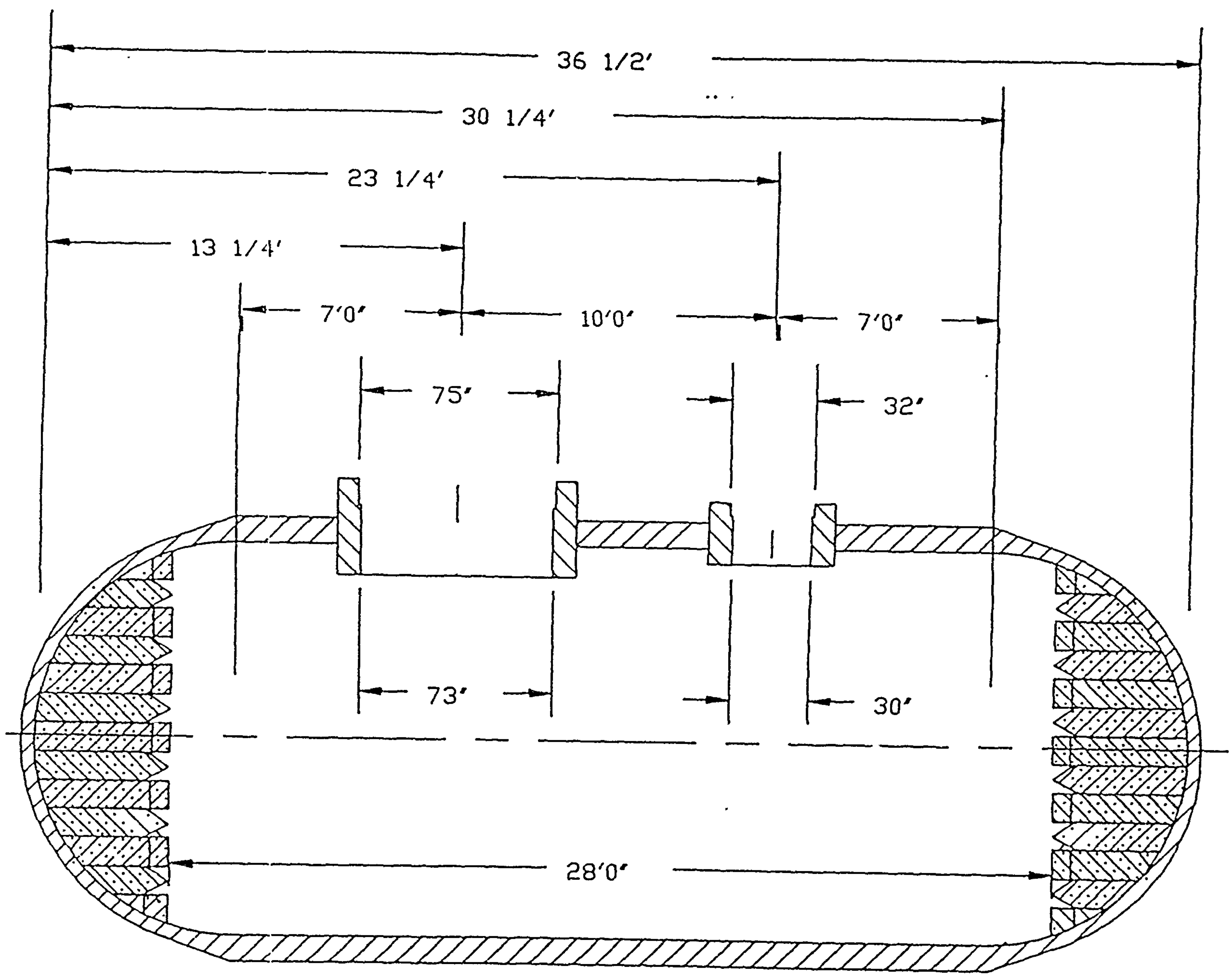
Fig. 21. Wavenumber calibrator.

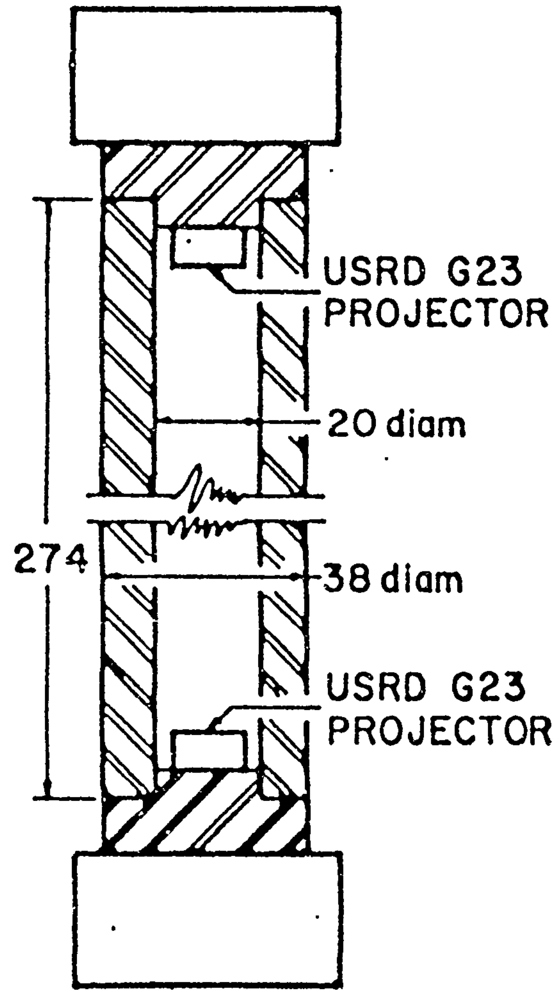
Fig. 22. New precision measurement system.

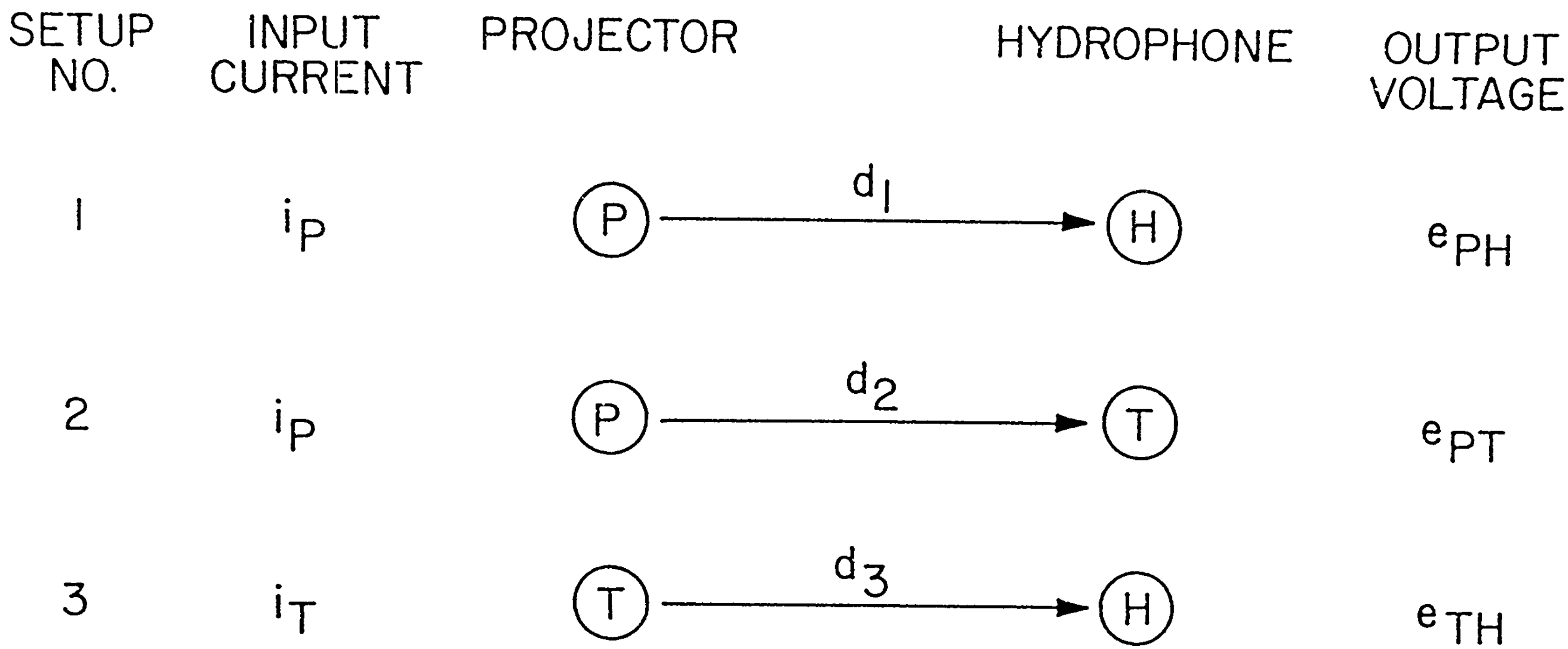


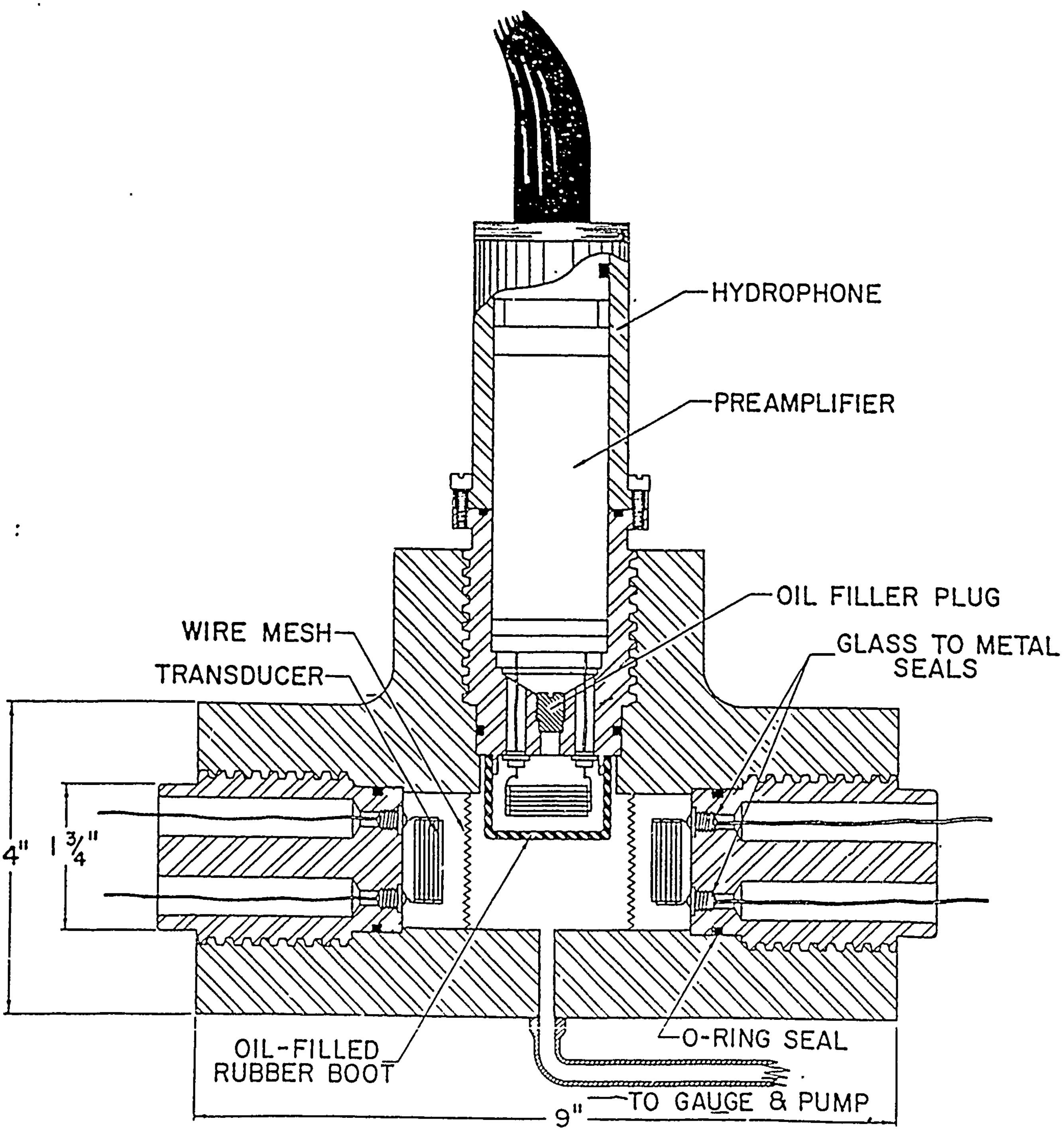


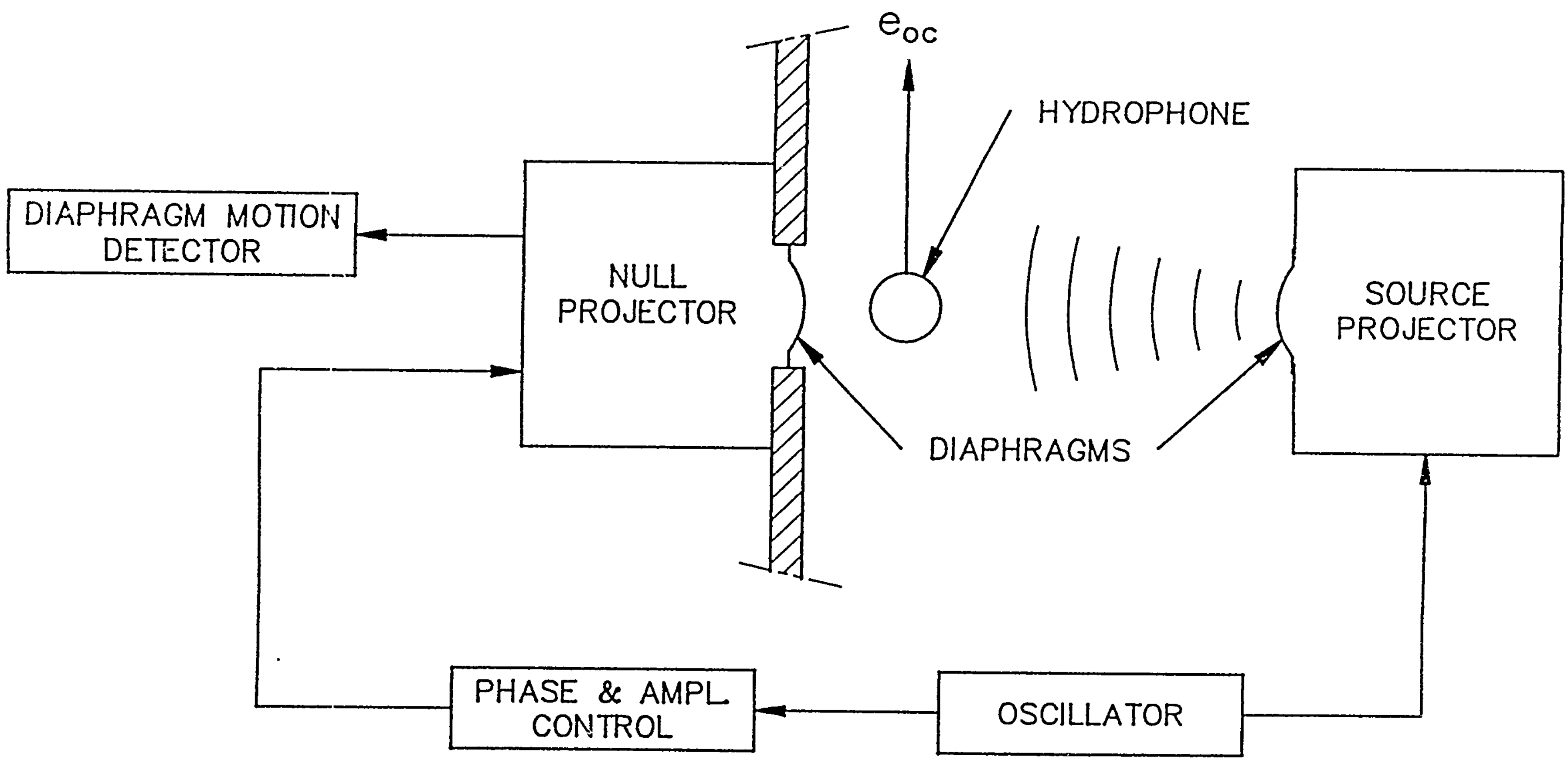
ALL DIMENSIONS IN CENTIMETERS

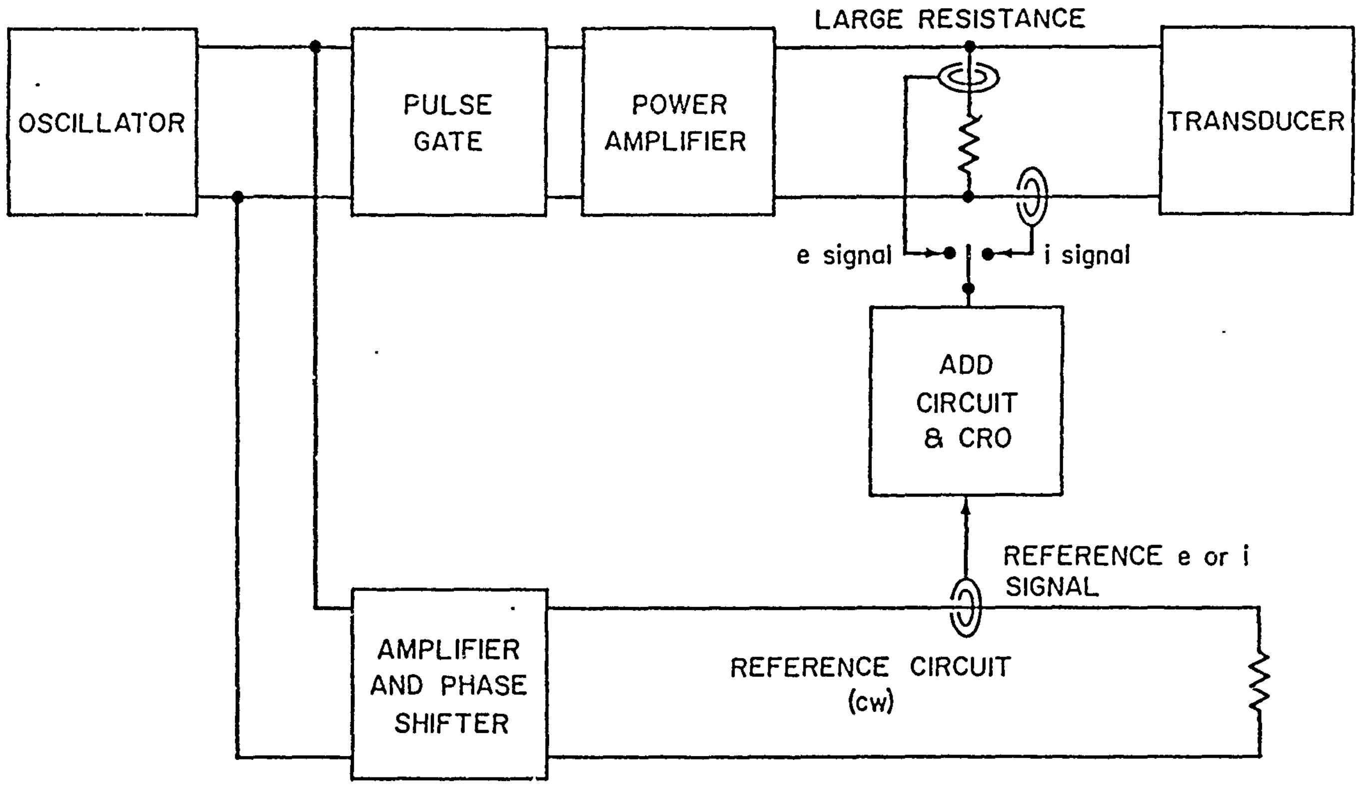

36 1/2'
30 1/4'
23 1/4'
13 1/4'
7'0"
10'0"
7'0"
75"
32"
73"
30"
28'0"


USRD G23
PROJECTOR
20 diam
274
38 diam
USRD G23
PROJECTOR

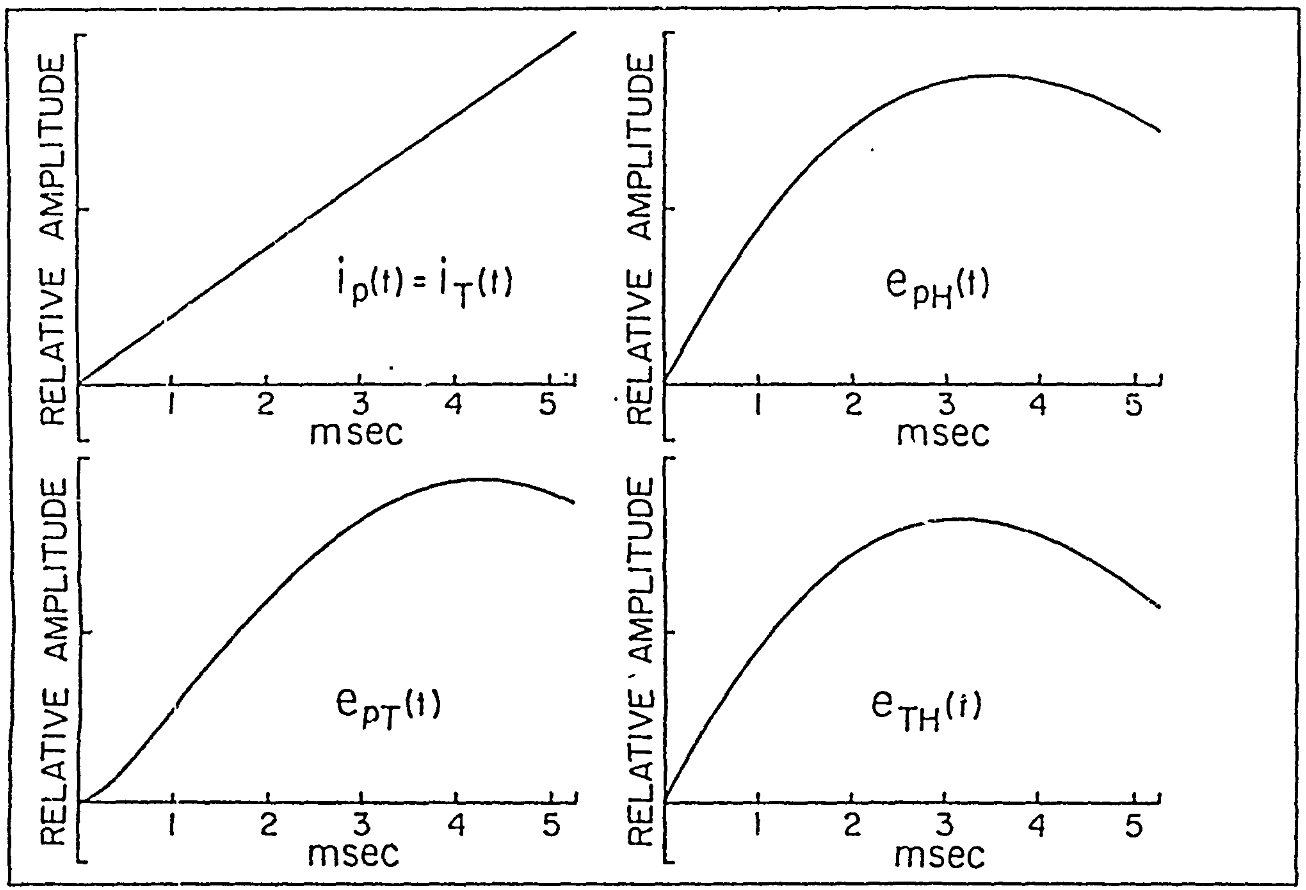

SETUP NO.
INPUT CURRENT
PROJECTOR
HYDROPHONE
OUTPUT VOLTAGE
1
i_P
P
d_1
H
e_{PH}
2
i_P
P
d_2
T
e_{PT}
3
i_T
T
d_3
H
e_{TH}

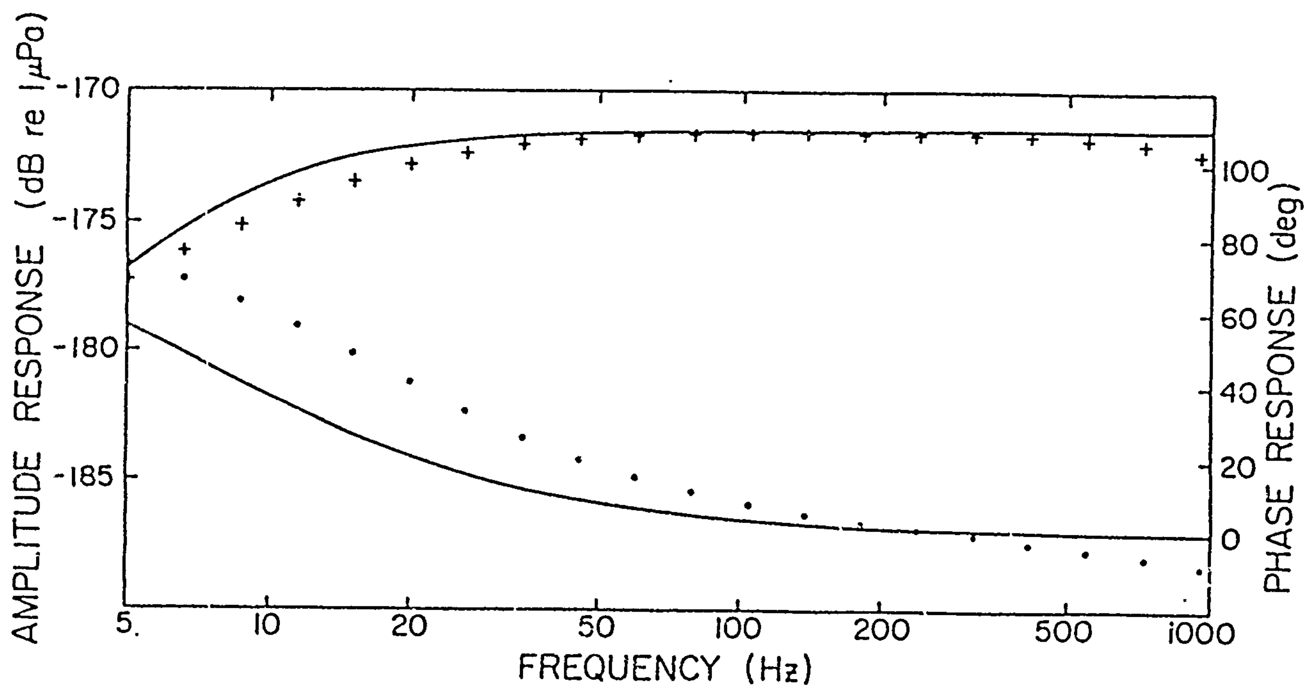

HYDROPHONE
PREAMPLIFIER
OIL FILLER PLUG
WIRE MESH
TRANSDUCER
GLASS TO METAL SEALS
4"
1 3/4"
O-RING SEAL
OIL-FILLED RUBBER BOOT
TO GAUGE & PUMP
9"


e_oc
HYDROPHONE
DIAPHRAGM MOTION DETECTOR
NULL PROJECTOR
SOURCE PROJECTOR
DIAPHRAGMS
PHASE & AMPL. CONTROL
OSCILLATOR

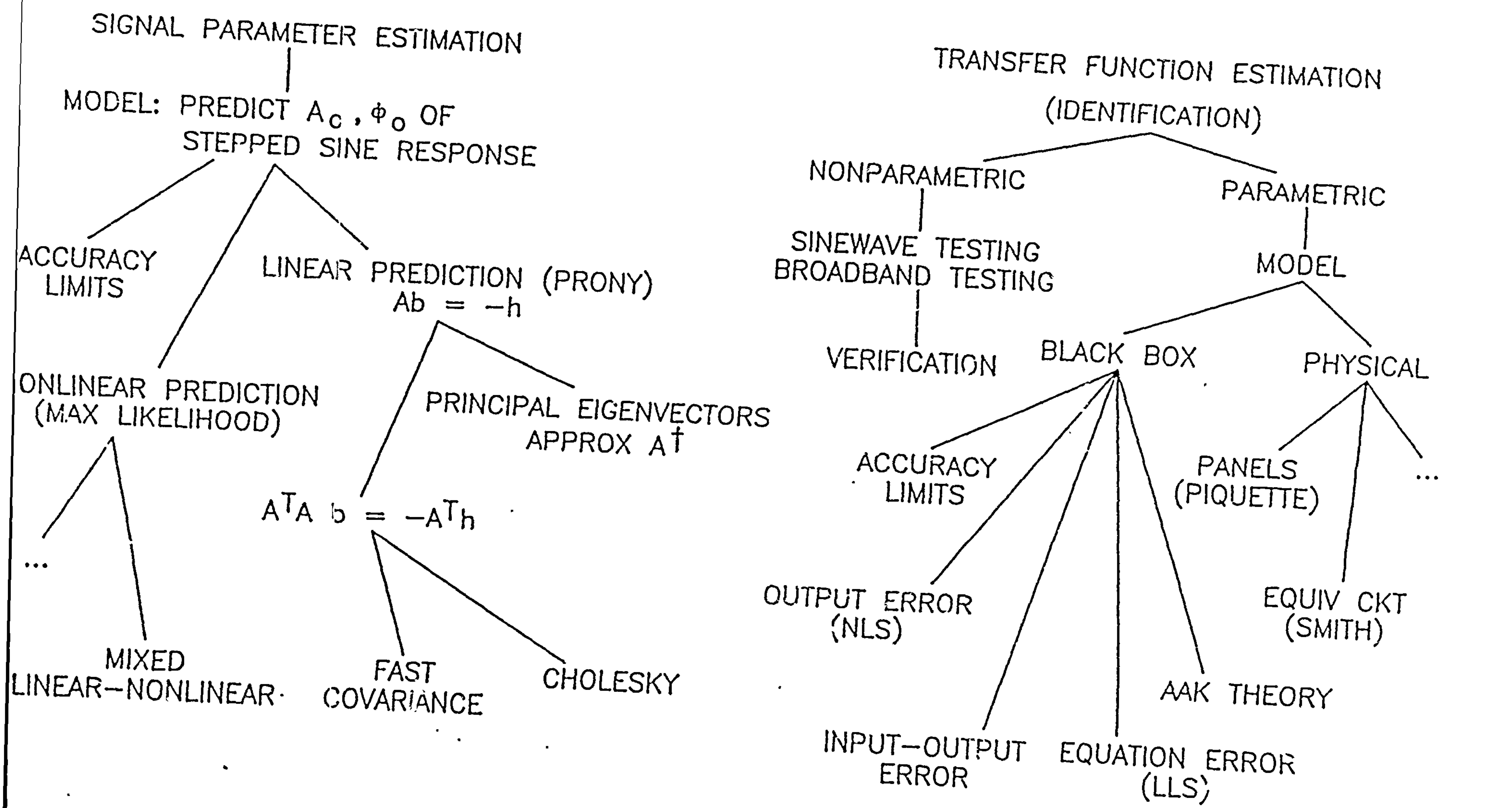


OSCILLATOR
PULSE GATE
POWER AMPLIFIER
LARGE RESISTANCE
TRANSDUCER
e signal
i signal
ADD CIRCUIT & CRO
REFERENCE e or i SIGNAL
AMPLIFIER AND PHASE SHIFTER
REFERENCE CIRCUIT (cw)

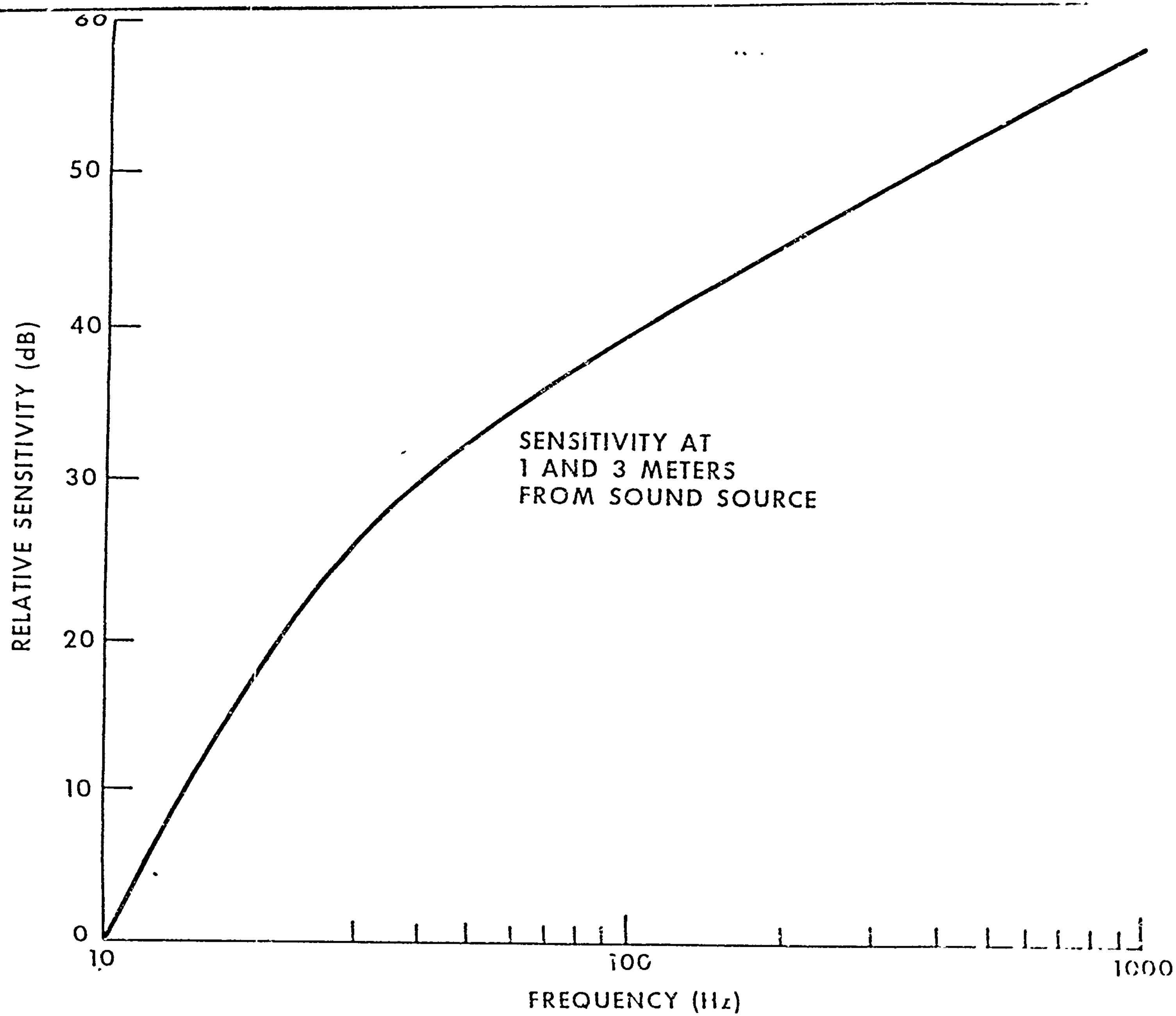

RELATIVE AMPLITUDE
$i_p(t) = i_T(t)$
1 2 3 4 5
msec
RELATIVE AMPLITUDE
$e_{pH}(t)$
1 2 3 4 5
msec
RELATIVE AMPLITUDE
$e_{pT}(t)$
1 2 3 4 5
msec
RELATIVE AMPLITUDE
$e_{TH}(t)$
1 2 3 4 5
msec

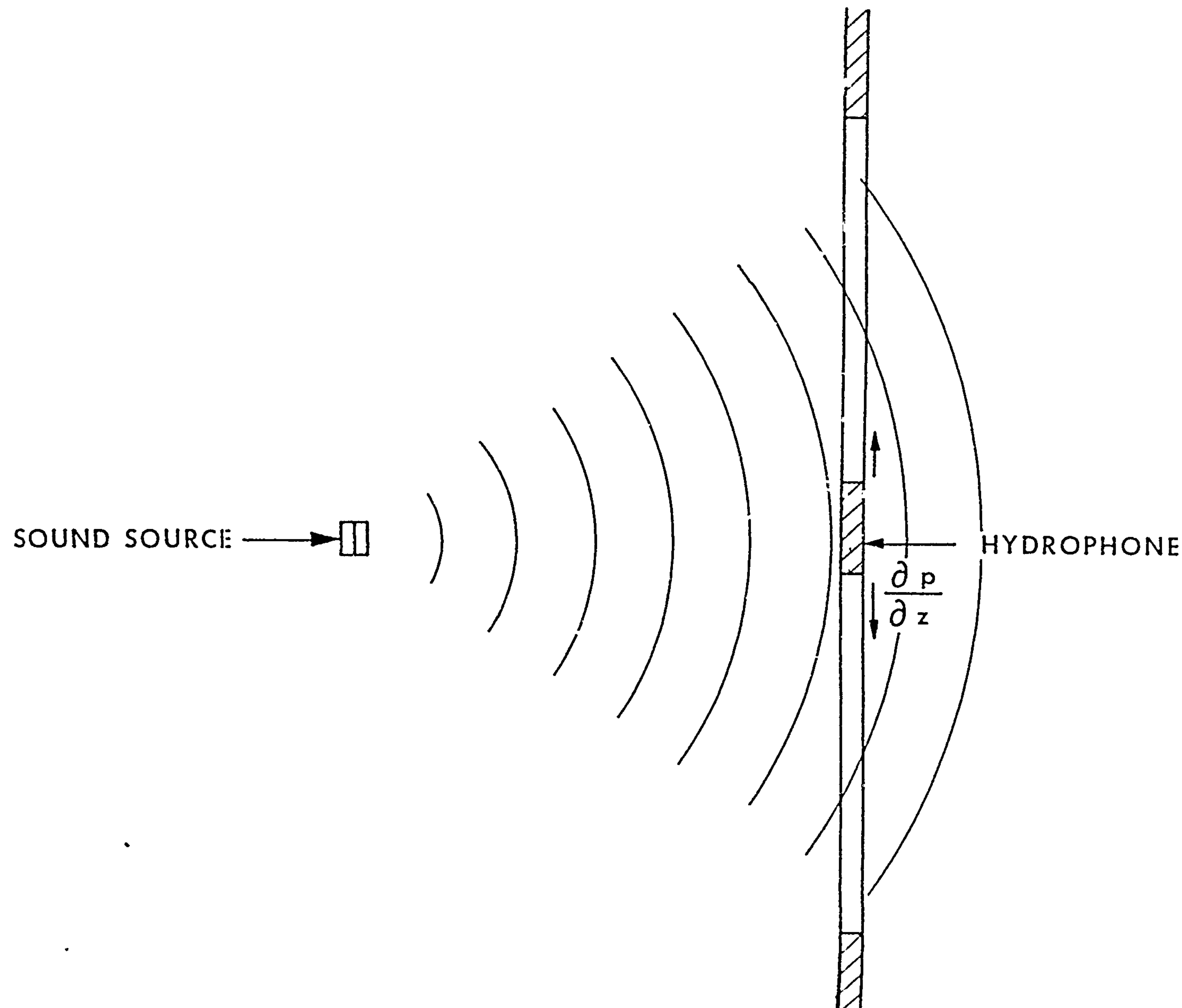


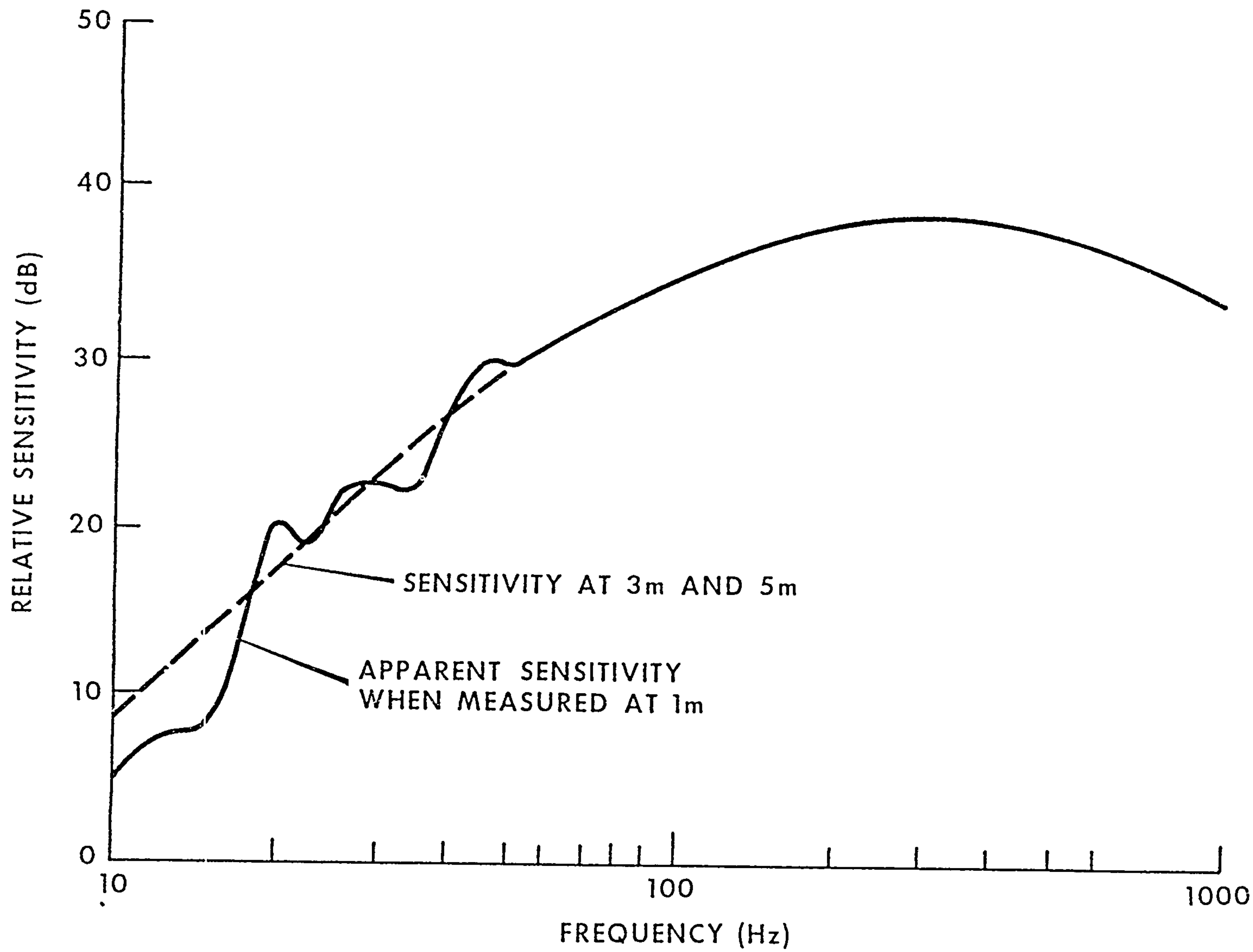
AMPLITUDE RESPONSE (dB re 1 μPa)
-170
-175
-180
-185
PHASE RESPONSE (deg)
100
80
60
40
20
0
5.
10
20
50
100
200
500
1000
FREQUENCY (Hz)

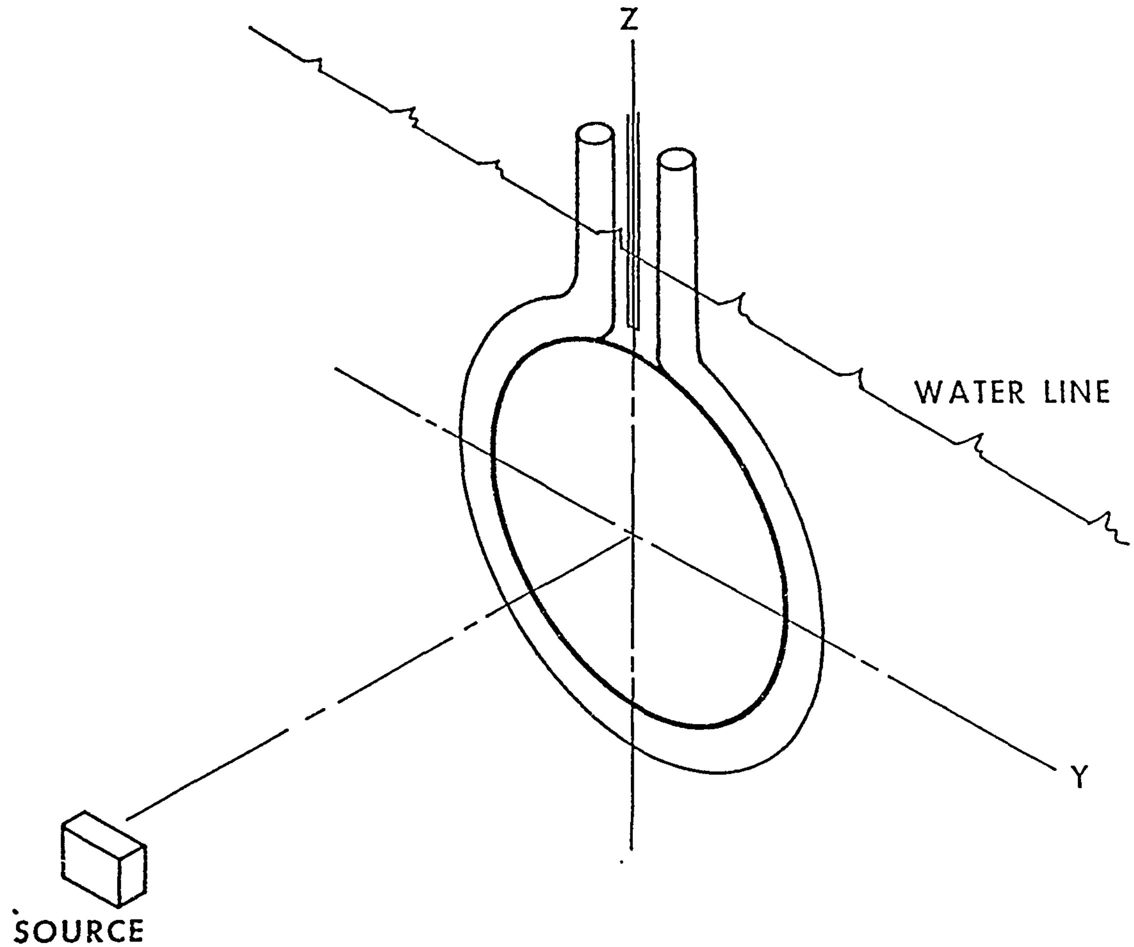

SIGNAL PARAMETER ESTIMATION
MODEL: PREDICT A_c, Φ_o OF STEPPED SINE RESPONSE
ACCURACY LIMITS
LINEAR PREDICTION (PRONY) $Ab = -h$
ONLINEAR PREDICTION (MAX LIKELIHOOD)
PRINCIPAL EIGENVECTORS APPROX $A^{\dagger}$
$A^TA\ b = -A^Th$
...
MIXED LINEAR–NONLINEAR
FAST COVARIANCE
CHOLESKY
TRANSFER FUNCTION ESTIMATION (IDENTIFICATION)
NONPARAMETRIC
PARAMETRIC
SINEWAVE TESTING BROADBAND TESTING
MODEL
VERIFICATION
BLACK BOX
PHYSICAL
ACCURACY LIMITS
PANELS (PIQUETTE)
...
OUTPUT ERROR (NLS)
EQUIV CKT (SMITH)
AAK THEORY
INPUT–OUTPUT ERROR
EQUATION ERROR (LLS)

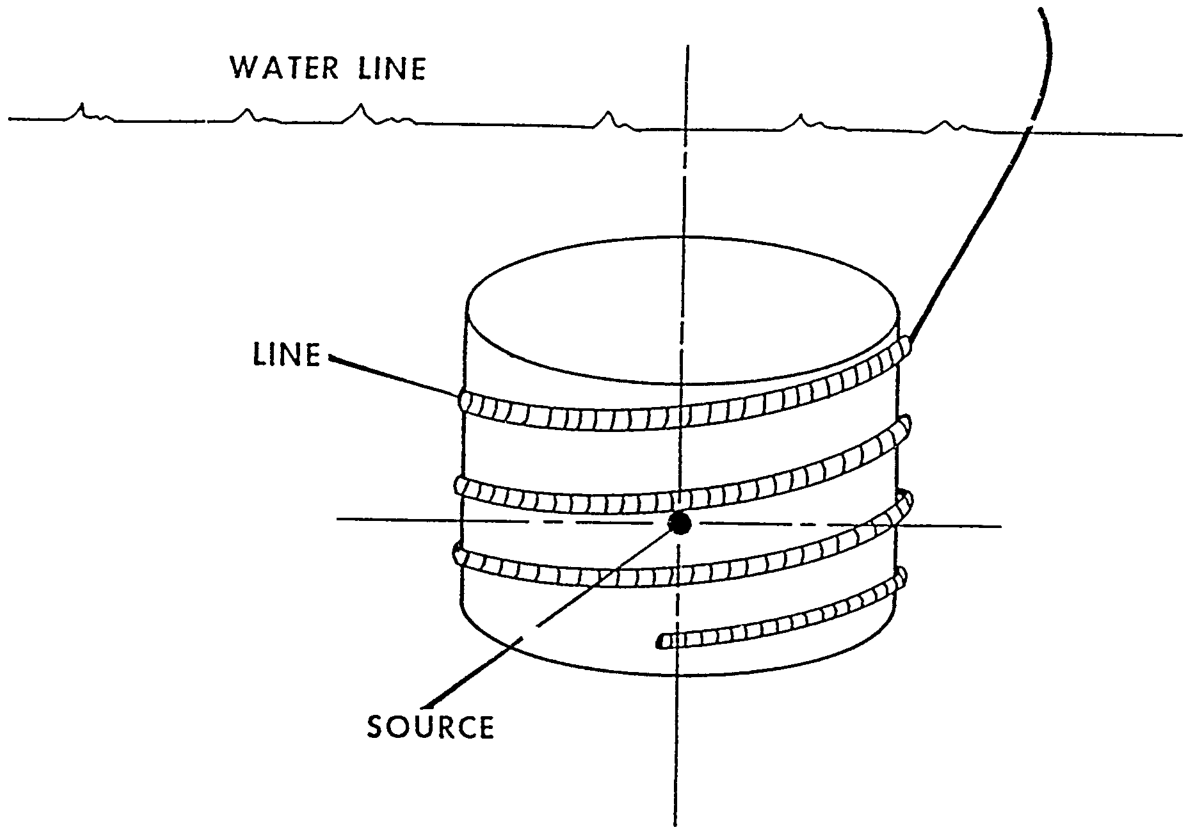
60

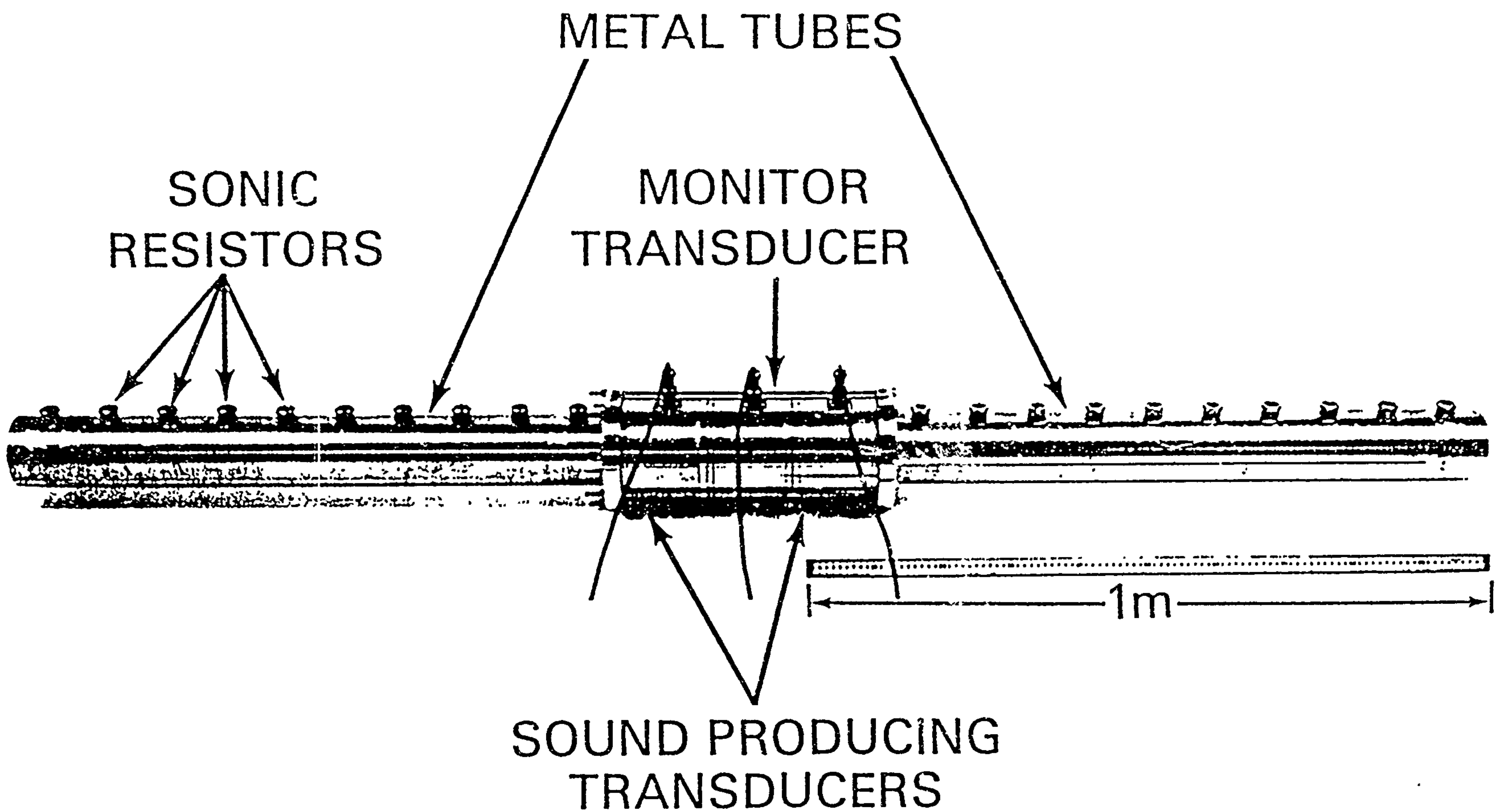

60
50
40
30
20
10
0
RELATIVE SENSITIVITY (dB)
SENSITIVITY AT
1 AND 3 METERS
FROM SOUND SOURCE
10
100
1000
FREQUENCY (Hz)

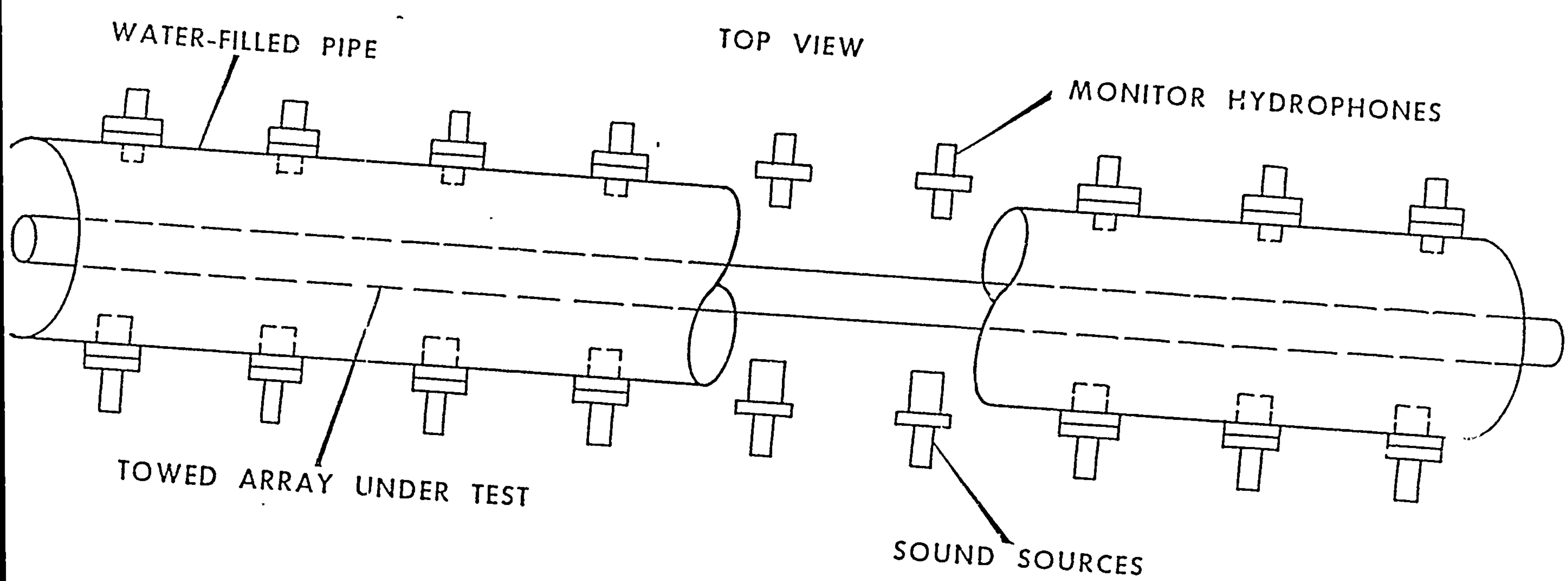

SOUND SOURCE
HYDROPHONE
$\frac{\partial p}{\partial z}$

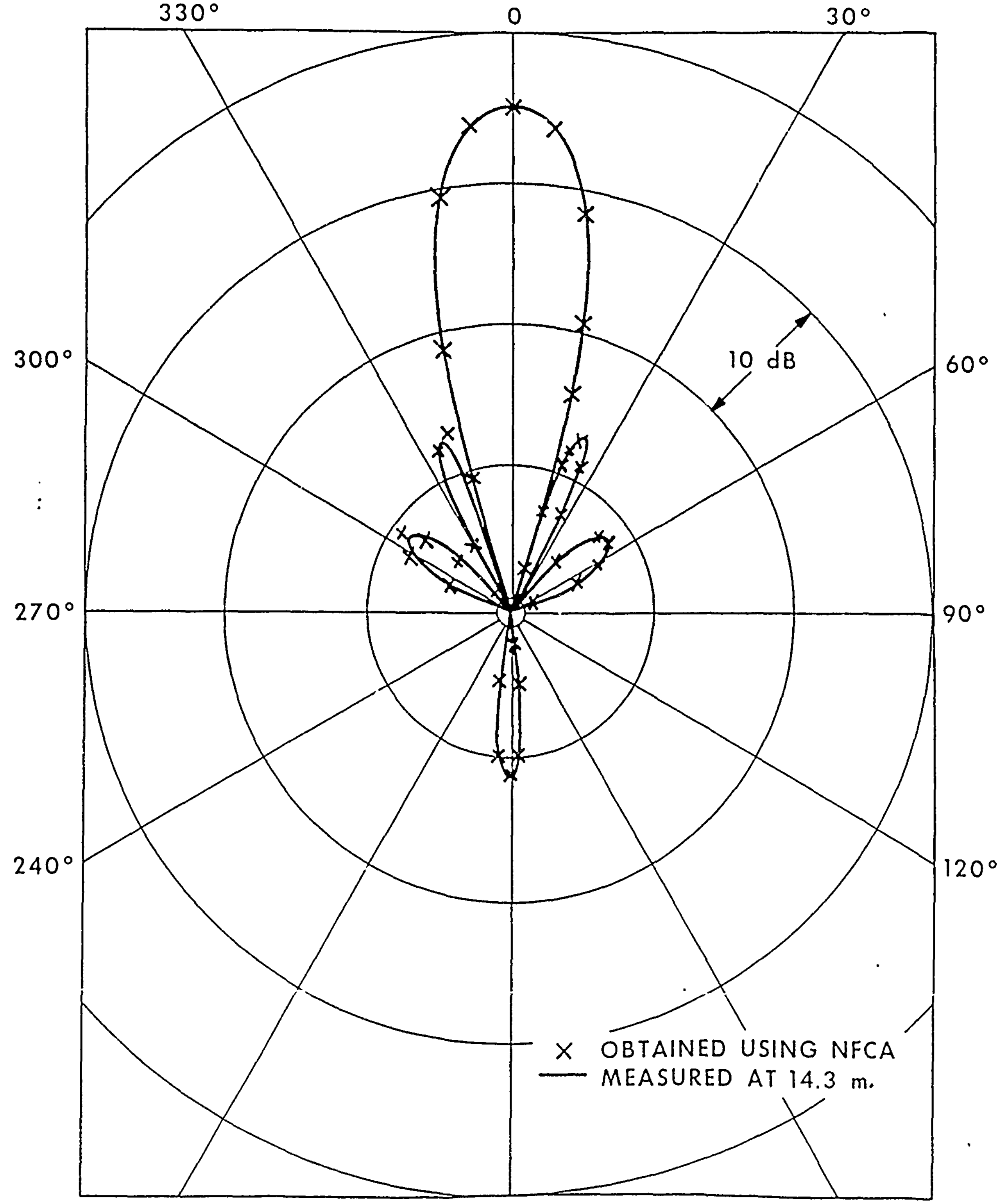

RELATIVE SENSITIVITY (dB)
50
40
30
20
10
0
10
100
1000
FREQUENCY (Hz)
SENSITIVITY AT 3m AND 5m
APPARENT SENSITIVITY
WHEN MEASURED AT 1m


Z
WATER LINE
Y
SOURCE

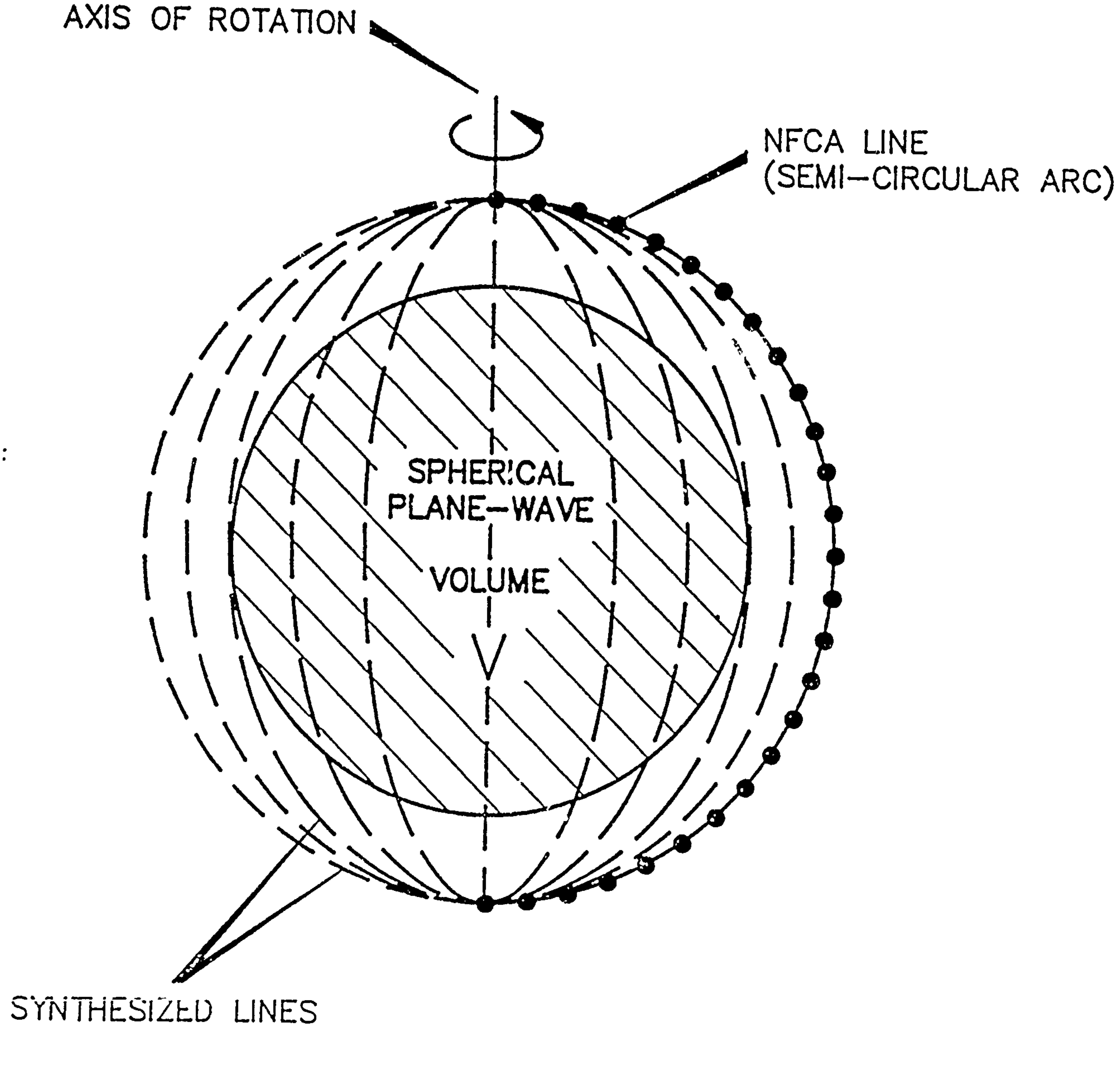

WATER LINE
LINE
SOURCE

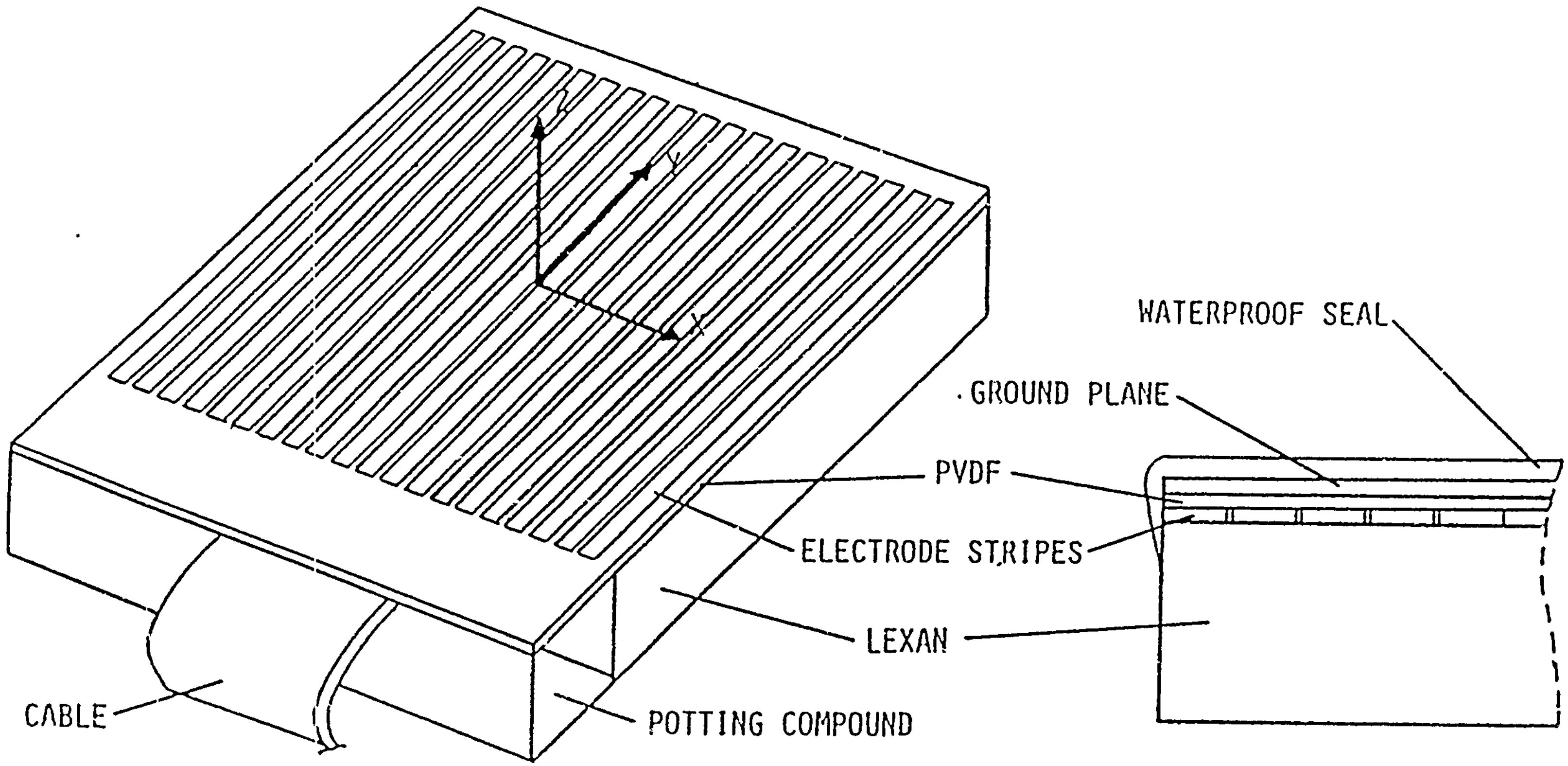

METAL TUBES
SONIC RESISTORS
MONITOR TRANSDUCER
1m
SOUND PRODUCING TRANSDUCERS

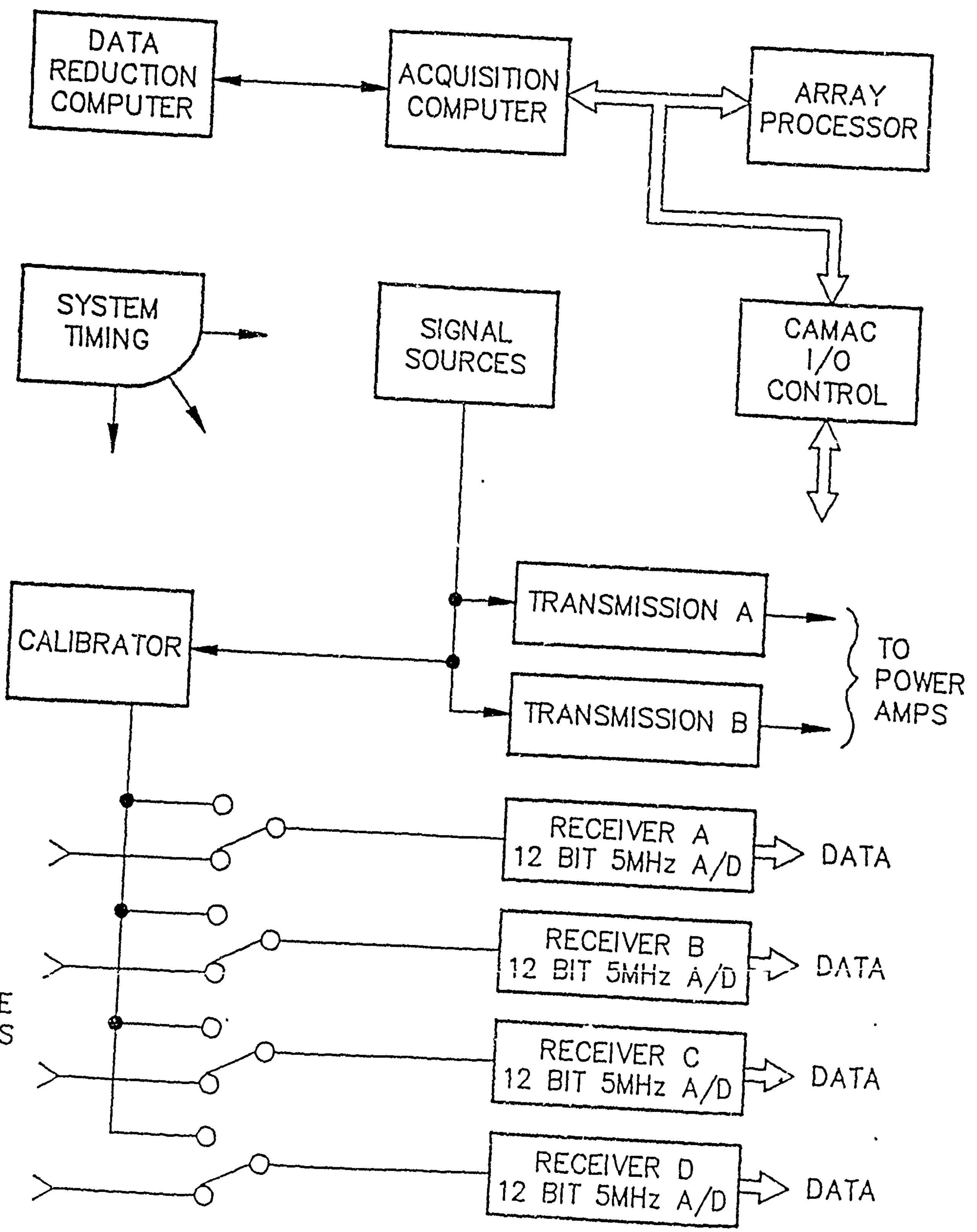

WATER-FILLED PIPE
TOP VIEW
MONITOR HYDROPHONES
TOWED ARRAY UNDER TEST
SOUND SOURCES



330°
0
30°
300°
10 dB
60°
270°
90°
240°
120°
210°
180°
150°
X OBTAINED USING NFCA
MEASURED AT 14.3 m.


AXIS OF ROTATION
NFCA LINE
(SEMI-CIRCULAR ARC)
SPHERICAL
PLANE-WAVE
VOLUME
SYNTHESIZED LINES


WATERPROOF SEAL
GROUND PLANE
PVDF
ELECTRODE STRIPES
LEXAN
CABLE
POTTING COMPOUND



DATA REDUCTION COMPUTER
ACQUISITION COMPUTER
ARRAY PROCESSOR
SYSTEM TIMING
SIGNAL SOURCES
CAMAC I/O CONTROL
CALIBRATOR
TRANSMISSION A
TRANSMISSION B
TO POWER AMPS
RECEIVER A 12 BIT 5MHz A/D
DATA
RECEIVER B 12 BIT 5MHz A/D
DATA
RECEIVE SIGNALS
RECEIVER C 12 BIT 5MHz A/D
DATA
RECEIVER D 12 BIT 5MHz A/D
DATA

45